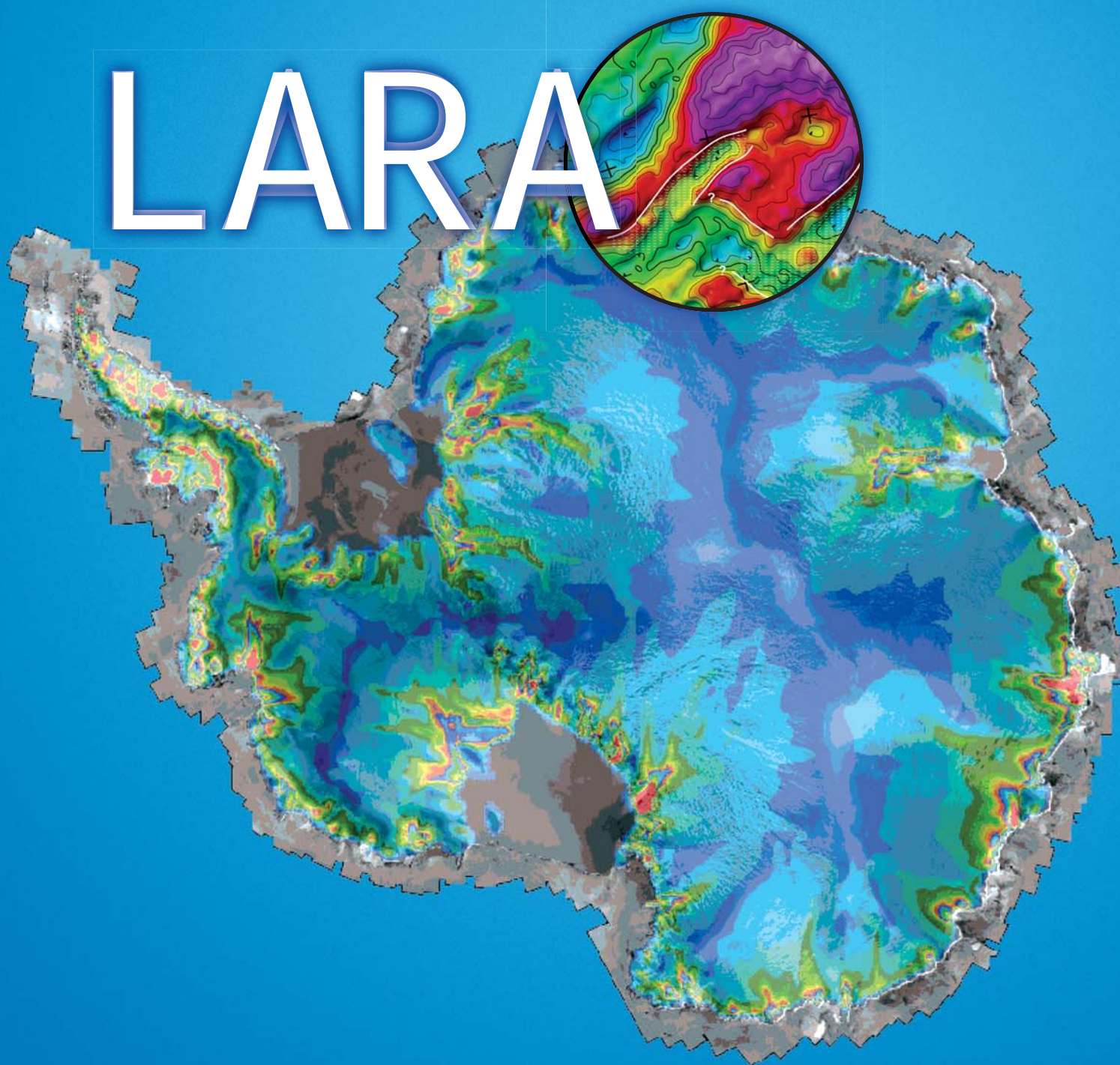


SCIENTIFIC OPPORTUNITIES  
FOR A LONG-RANGE AIRCRAFT  
FOR RESEARCH IN ANTARCTICA

LARA



## ACKNOWLEDGMENTS

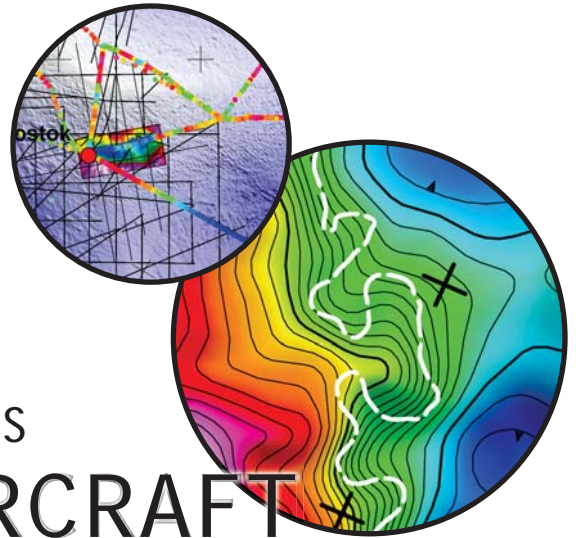
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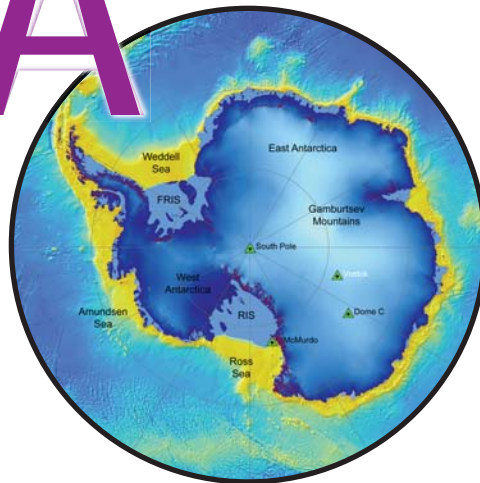
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SCIENTIFIC OPPORTUNITIES  
FOR A **LONG-RANGE AIRCRAFT**  
FOR RESEARCH IN ANTARCTICA

**LARA**



REPORT OF A WORKSHOP HELD  
SEPTEMBER 27-29, 2004



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# Executive Summary

The polar regions play a critical role in Earth's climatic and geodynamic systems. Although located far from the main centers of human civilization, the polar atmosphere and oceans have strong global connections and therefore directly affect global weather, climate, and the world's population. Over geologic time scales, Antarctic geodynamic processes are a major influence on ice-sheet dynamics and global environmental change, which affects current and long-term, large-scale sea-level changes.

Currently, we have a physically based, conceptual understanding of many of the significant interactions that impact climate and the Antarctic environment. To transform this conceptual understanding into quantitative knowledge, it is necessary to acquire geographically diverse sets of fundamental observations at a range of spatial and temporal resolutions. Satellite data provide needed continent-wide coverage, but they often have limited spatial resolution and provide virtually no sub-surface information. They also require extensive calibration and validation, which can be difficult or impossible to obtain in the Antarctic. Data collected from remote field camps, seagoing vessels, and small aircraft

provide only point sources of information on a continental scale. The mobile research platforms currently in use lack the capability to sample rapidly enough to include the daily to weekly time scale of atmospheric and oceanic processes over continent-wide scales. The spatial-scale gap and temporal-scale gap in data collection can best be filled by a long-range, ski-equipped aircraft dedicated to Antarctic research.

To address these data gaps, the Antarctic solid Earth, glaciology, atmospheric science, and oceanographic communities came together at a workshop in September 2004 in Herndon, Virginia. At the workshop, they formulated a scientific justification for a long-range research aviation facility and identified key scientific questions that need to be addressed (Table 1). Target areas extend over both continental and oceanic regions. Different survey designs and sensor configurations are required to address each key question. Workshop participants defined several generic mission profiles that would achieve most scientific goals.

Common to all mission profiles is the need for an aircraft capable of carrying an integrated payload of remote-sensing and *in situ* instrumentation over long distances.

Almost all mission profiles require data acquisition in regions more than a thousand nautical miles from existing landing sites for wheeled aircraft in Antarctica. To get to the target area and be able to survey for several hours requires aircraft endurance of at least 10 hours or the ability to refuel in remote locations. Flights that maintain altitudes from a few hundred meters to at least 7 km are required. Atmospheric physics and chemistry research require a long-range aircraft with significant load-carrying capability. Payload requirements range from 2,500 lbs for solid Earth and glaciology missions to 12,000 lbs for atmospheric chemistry missions.

The range of instrumentation that needs to be supported, and the wide variety of data that will be collected, by a multidisciplinary, instrumented, long-range research aircraft creates operational complexity, which requires a central management and operations facility. Existing research aviation facilities generally do not cover the broad range of disciplines represented at the workshop and do not support the variety of sensors envisioned for the long-range Antarctic research aviation facility. The development and operation of such a facility would be a unique undertaking.

Table 1. Key Questions

Geology and Geophysics	What are the interactions between the tectonic and climatic evolution of Antarctica?
	What are the distribution, nature, and origin of sub-glacial lakes and what is their relation to crustal structure and heat flow?
	What is the volume of the ice sheets and the range of sea-level fluctuations on different time scales?
	What role did East Antarctica play in the Precambrian continental growth process?
	What was the timing and magnitude of Mesozoic to Cenozoic extension in Antarctica and how did it affect the global plate-motion circuit?
Glaciology	What is the relationship between climate change and the ice sheets?
	What are the controls and interactions governing ice-sheet dynamics?
	What are the distribution, nature, and interconnection of sub-glacial lakes?
	What are the current dynamics of coastal areas?
Oceanography	What is the interannual variation in sea-ice thickness on a basin-wide scale?
	What role does water densification in polynyas and beneath ice shelves play in the global ocean meridional overturning circulation?
	How does deep-ocean water temperature vary over interannual scales?
	Over what distances does sea ice drift in the Antarctic Zone from the time it forms to when it fully melts?
	What role do marginal ice zones play in physical and biological activity?
Atmospheric Sciences	What role does the Antarctic atmospheric heat sink play in global climate?
	How does the mountainous topography of Antarctica impact the global atmospheric circulation?
	What role do the Antarctic ice sheets play in global sea-level variations?
	What is the nature of air-sea interactions over the Southern Ocean?
	How is the chemistry of the high southern latitudes tied to Antarctic atmospheric circulation?



# 1. Introduction

## 1.1. MOTIVATION

Aircraft are an integral component of the complex logistical system necessary for research in the Antarctic. They are essential for transport of personnel and supplies to and from the continent, and among permanent stations and temporary research sites on the continent. Aircraft are used, often in conjunction with ground-based stations and transportation, as platforms from which to carry out research on the vast expanses of snow and ice that comprise both the Antarctic continent and the surrounding ocean. Seagoing vessels contribute to Antarctic science by providing logistical support for near-coastal stations and by providing platforms for research on the ice-covered portion of the Southern Ocean. Data from a variety of polar-orbiting satellites contribute to our ability to gather information, especially on the continental ice cap, in the atmosphere, and on the seasonally varying sea-ice cover.

Platforms now used for research in the Antarctic have served us well, allowing for the success of a large number of research projects focused on continental, atmospheric, and oceanic processes. Our knowledge

has, however, advanced to an extent beyond which progress is increasingly limited by the range of available research platforms, especially over the Antarctic continent, but also over the surrounding ocean. Detailed observational programs suitable for process studies are carried out over restricted areas, their extents limited by the range of the terrestrial transportation and small aircraft used to reach outward from research stations or seagoing vessels. Use of temporary terrestrial research stations is limited by logistical constraints such as aircraft range and insufficient landing facilities for wheeled aircraft. Consequently, our understanding of the Antarctic geophysical environment is limited primarily to regions around major stations such as McMurdo. A large swath of East Antarctica remains virtually *terra incognita* because we are unable to reach it using available aircraft. Further, present temporary stations can only provide information in a piecemeal fashion; to study a time-varying and dynamic feature such as the ice sheet, or the surrounding ocean and its sea-ice cover, data must be collected simultaneously. Polar-orbiting satellites provide some types of surface information continuously

over the entire continental and oceanic region, but do not provide the subsurface information necessary to understand the underlying processes. Missing from the current array of platforms available to the Antarctic research community is an instrumented, long-range aircraft for observing the Antarctic in its entirety.

Many nations use aircraft as research platforms for polar science. During the 1970s, the United States, United Kingdom, and Denmark used an LC-130 for aerogeophysical mapping of large parts of Antarctica and for atmospheric science. Since the loss of the science LC-130 in 1987, our picture of the geology and geophysics of East Antarctica has not evolved much and the lack of a research platform has had a devastating impact on atmospheric sciences research in Antarctica. Over the past several years, both the solid Earth and atmospheric science communities held several workshops that considered the possibility of using aircraft as a research platform. Triggered by the loss of the Support Office for Airborne Research (SOAR) aerogeophysical facility in 2001, the solid Earth and glaciology community met at the REMote Views and Exploration of Antarctic Lithosphere

(REVEAL) workshop in 2002 to discuss the need for a new facility. This workshop was followed by the FASTDRILL, Structure and Evolution of the Antarctic Plate (SEAP), and Frontiers and Opportunities in Antarctic Geosciences workshops that all concluded that aerogeophysical mapping is crucial for advancing geological and glaciological research in Antarctica. For the atmospheric science community, efforts associated with the Antarctic Ross Island Meteorology Experiment (RIME) and the Antarctic Tropospheric Chemistry Investigation (ANTCI) projects, together with the decision that the NSF/NCAR C-130Q cannot operate out of McMurdo, led to the conclusion that an Antarctic long-range research aviation facility is needed to achieve the key scientific goals outlined in these projects. The growing interest in an airborne research platform in the solid Earth, glaciology, atmospheric science, and oceanography communities over the past several years resulted in the planning of the Scientific Opportunities for a Long-Range Aircraft for Research in Antarctica (LARA) workshop that brought together scientists to formulate a scientific justification for a long-range research aviation facility.

## 1.2. WORKSHOP OBJECTIVES

From September 27-29, 2004, the National Science Foundation (NSF) Office of Polar Programs sponsored

the LARA workshop on scientific opportunities for a multidisciplinary research aircraft for Antarctic research at the Days Inn and Conference Center in Herndon, Virginia. The LARA Steering Committee advertised and organized the workshop. Participation was open to everyone interested. More than 60 research scientists, broadly representing Antarctic solid Earth sciences, glaciology, physics and chemistry of the atmosphere, and oceanography, attended the workshop (Appendix 1). The overall goal of the workshop was to: (1) identify the key scientific questions in Antarctic science that currently cannot be addressed because of a gap in our observational capabilities; (2) develop a strong scientific justification for the required new research tools; and (3) provide NSF with recommendations on the requirements for a long-range research aviation facility.

## 1.3. WORKSHOP AGENDA

The morning of the first day of the workshop was devoted to keynote presentations for each discipline, followed by a short discussion (Appendix 2). This session was intended to give an overview of each discipline's key scientific questions and was targeted mainly for scientists outside the speaker's particular discipline. Together with a poster session after lunch (Appendix 3; also see <http://polarmet.mps.ohio-state.edu/>

for oral presentations and poster abstracts), the keynote presentations served as a catalyst for afternoon discussions in four breakout groups. The goal of the breakout group discussions was to identify the most urgent scientific questions in geology and geophysics, glaciology, oceanography, and atmospheric sciences that can only be addressed using a long-range research aircraft. The second day of the workshop began with presentations by the breakout groups' discussion leaders from the previous day. Each 15-minute talk summarized key scientific questions identified by the breakout groups and specified the capabilities and data sets needed to address these questions. Each talk was followed by 10 minutes of discussion. During late morning of the second day, participants presented examples demonstrating the capabilities of, and opportunities for, research aircraft. This session included talks on possible instrumentation of a long-range aircraft. The afternoon of the second day focused on an overview of existing research aviation facilities and models for management structure. Later in the afternoon, a panel-led discussion focused on the desired facility models and instrumentation. The last day of the workshop started with two invited talks from aircraft operators representing the Polar Research Support Section. This session was intended to give scientists an overview of aircraft operations and safety considerations for

polar research aircraft and to address issues that will be important to the production of a research aircraft. The final set of talks focused on data policies, data management, and data archiving. The workshop concluded at noon on the third day.

Prior to the workshop, preliminary scientific goals for each discipline were distributed over the workshop website; a web-based discussion forum was set up to give non-participating scientists an opportunity to provide input. The findings and recommendations in this report reflect the discussions and conclusions from the workshop and the web-based input.

## 2. Scientific Targets for LARA

### 2.1. ANTARCTIC GEOLOGY AND GEOPHYSICS

#### 2.1.1. SCOPE AND RELEVANCE

Antarctica is a key element in Earth's geodynamic and climatic systems. The present-day Antarctic continent played a central role in the formation and break-up of both the Rodinia and Gondwana supercontinents. The early Cenozoic break-up of Gondwana resulted in a major rearrangement of the continental masses, which isolated Antarctica from mid-latitude oceanic influences by establishing the Antarctic Circumpolar Current (ACC). This event was largely responsible for development of the West and East Antarctic Ice Sheets (WAIS and EAIS) that blanket 98% of the continent and fundamentally influence world climate today. Despite the strong links of Antarctica to the global geodynamic and climatic systems and the central role that Antarctica has played in shaping the present global environment, its kinematic relationship to the global plate circuit and its role as substrate to the world's major ice sheets remain in question.

Present understanding of the Antarctic continent's geologic and

tectonic development is largely derived from sparse rock outcrops along its perimeter. Knowledge of the geological structures from surrounding continents, such as Australia, southern Africa, and South America, complements the limited geologic information of vast parts of Antarctica. To date, geophysical mapping of the ice-covered continent's interior has been limited to reconnaissance expeditions during the International Geophysical Year in 1957, isolated over-ice traverses, and aerogeophysical profiling projects funded by the United States, United Kingdom, Denmark, and Russia during the 1970s using LC-130 and Ilyushin long-range aircraft. In recent years, a few small-scale aerogeophysical transects reaching into the interior of East Antarctica have provided important constraints for unraveling the tectonic development and geologic structure of parts of the East Antarctic shield. Nevertheless, on the eve of the 50<sup>th</sup> anniversary of the International Geophysical Year, fundamental, first-order parameters such as bedrock elevation, lithology, structure, age, tectonic history, and

ice volume remain poorly known over large parts of the continent. Geological data from rock exposures along the East Antarctic margin indicate a deep history of tectonic events from >3.2 Ga to ~150 Ma that reflects major transformations in supercontinent evolution, yet detailed time-space models of past geologic events are presently beyond our grasp because of the vast ice cover.

Global geodynamics continues to be a major influence on the formation, nature, and dynamics of the ice sheets. For example, the mass balance and response of the WAIS to climate forcing appear to be strongly influenced by geologic and geophysical parameters such as the distribution of sedimentary basins and the geothermal heat flux into the base of the ice. Precambrian structures may have influenced the style and location of younger tectonic and magmatic events that are manifested by the major features of the continent today (Figure 1), such as the Paleozoic and Mesozoic orogens of the Transantarctic Mountains, Mesozoic rift zones, and Cenozoic



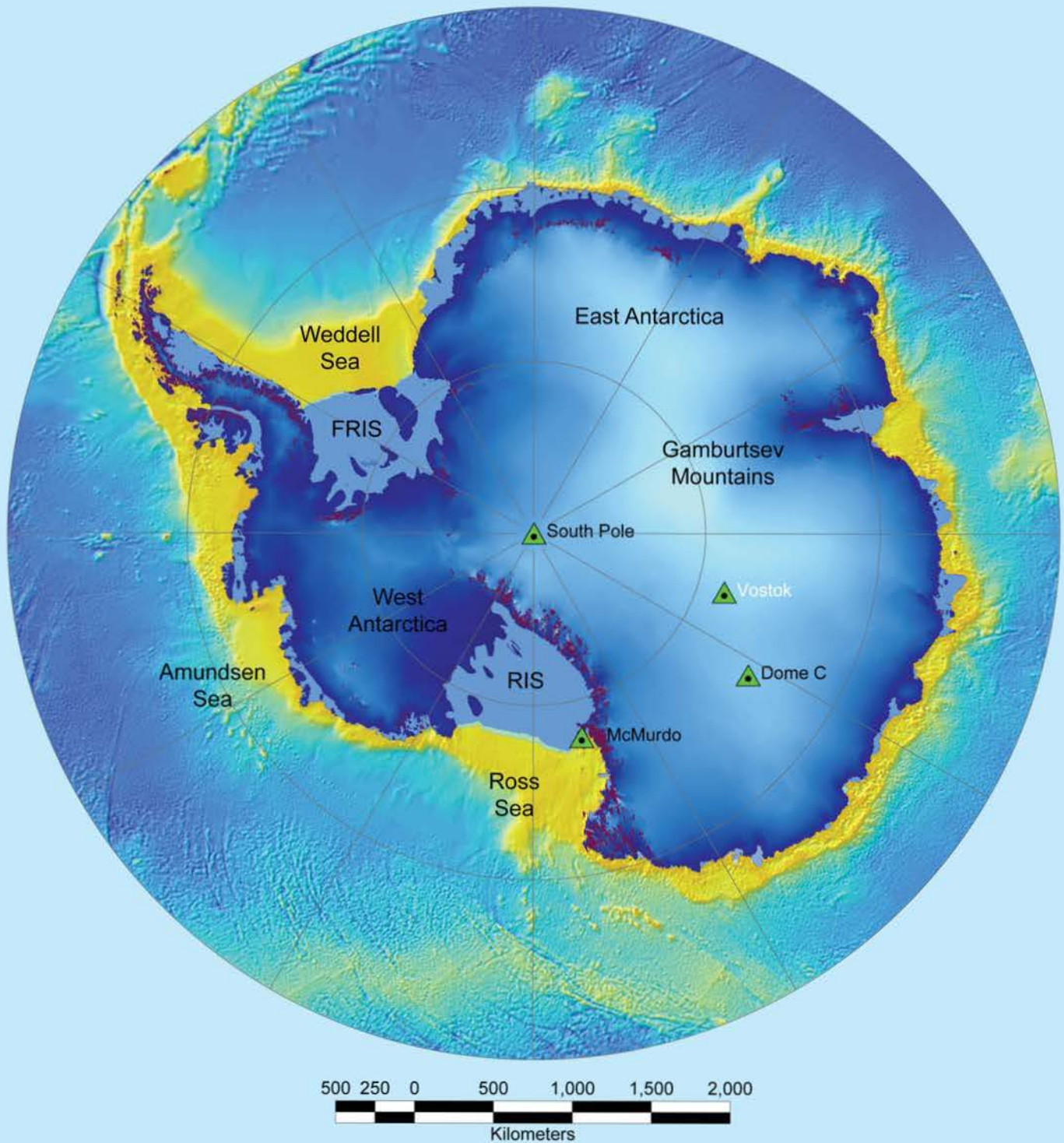


Figure 1. The Antarctic continent is divided by the Transantarctic Mountains, a lithospheric and morphologic boundary between the East Antarctic shield and West Antarctica, an assemblage of allochthonous crustal blocks. The difference between the cold cratonic lithosphere beneath East Antarctica and the hot lithosphere beneath the West Antarctic rift system with active volcanism is the basis for differences in the overlying ice sheet. The West Antarctic Ice Sheet is a marine-based ice sheet prone to instability, while the East Antarctic Ice Sheet is believed to be a long-lived, stable continental ice sheet. Black dots mark rock outcrops. FRIS, Filchner-Ronne Ice Shelf; RIS, Ross Ice Shelf. Image courtesy of M. Studinger (LDEO) using data from the Antarctic Digital Database project (ADD) and RAMP elevation data provided by the National Snow and Ice Data Center (NSIDC).

volcanic provinces. In turn, these events have influenced ice-sheet dynamics and, therefore, global climate.

The WAIS contains enough grounded ice to raise global sea level 5 m if it were to melt completely, and hosts ice streams that could potentially evacuate the ice over short geologic time scales. Recent measurements show that the ice sheet is undergoing rapid and dramatic change in some regions and reveal an ice-sheet-wide history of large fluctuations in extent and volume.

Although the EAIS is apparently more stable, it exerts a profound influence on global climate and covers numerous sub-glacial lakes that may have existed for millions of years. Major interest lies in the age of these lakes, their tectonic history, their resident biota, and the record of Antarctic climatic history that may be contained in the sediments beneath them.

Antarctica forms one of seven major lithospheric plates on Earth and is one of the six continents. It contains unique geologic localities such as the sub-glacial Lake Vostok hidden under 4 km of ice. However, fewer than 2% of the rocks are accessible. Given the extensive ice cover, airborne geophysical data (Figure 2) linked to field-based geologic mapping, ground-based geophysics, and petrologic, geochemical, and geochronologic analysis of outcrop and drillhole samples are the best means of characterizing broad areas of the Antarctic lithosphere. Without a

ski-equipped long-range research aircraft, progress in advancing a detailed structural framework of the Antarctic lithosphere will be slow.

### 2.1.2. KEY QUESTIONS

Many fundamental questions concerning the geologic and tectonic evolution of Antarctica remain. At the workshop, scientific goals and potential target areas were identified in the context of two major themes: (1) geology and ice-sheet dynamics and (2) crustal architecture and evolution of the unknown polar regions. Investigations directed at these themes will form the basis for an integrated, multidisciplinary initiative to study the relationship among Antarctic geodynamic processes, ice-sheet dynamics, and global environmental change. Although a conceptual understanding of these processes exists, it is essential to move towards quantitative models. The current lack of first-order data sets for most of Antarctica prevents us from taking this important step.

#### GEOLOGY AND ICE SHEET DYNAMICS

##### What are the geologic controls on ice-sheet dynamics?

Antarctic geologic processes drive ice-sheet dynamics and global environmental change, which affect current and long-term, large-magnitude sea-level changes. There are several

geologic controls on ice-sheet dynamics. Over the past 100 million years, plate kinematics resulted in isolation of the Antarctic continental lithosphere and evolution of the Southern Ocean, shaping paleotopography and pathways of ocean currents. Relative motion between East and West Antarctica resulted in rift basins and elevated topography, creating a unique continental polar environment for climate and ice-sheet evolution. More recent extensional tectonics formed rift basins and generated the high heat flow that continues to influence basal ice conditions. Identifying the three-dimensional geometry of rift basins and the location of sub-ice volcanoes will help clarify the relationship between tectonics and ice-sheet dynamics. Paleoclimate and ice-sheet modeling studies are hampered by incomplete knowledge and poor resolution of boundary conditions, including reconstructions of global and regional paleogeography, paleotopography, heat flow, distribution of sub-glacial sediments, and Cenozoic volcanic rocks.

##### What are the geodynamics of rifting in an ice-covered environment?

In turn, ice sheets can exert an influence on geodynamic processes. Rapid unloading of ice sheets may enhance magma production rates. The largest Cenozoic volcanoes in Antarctica are located at the edges of the EAIS and WAIS, where waxing and waning of the ice sheets are greatest.



What are the feedbacks between mountain uplift and the development and evolution of the Antarctic ice sheet and global climate?

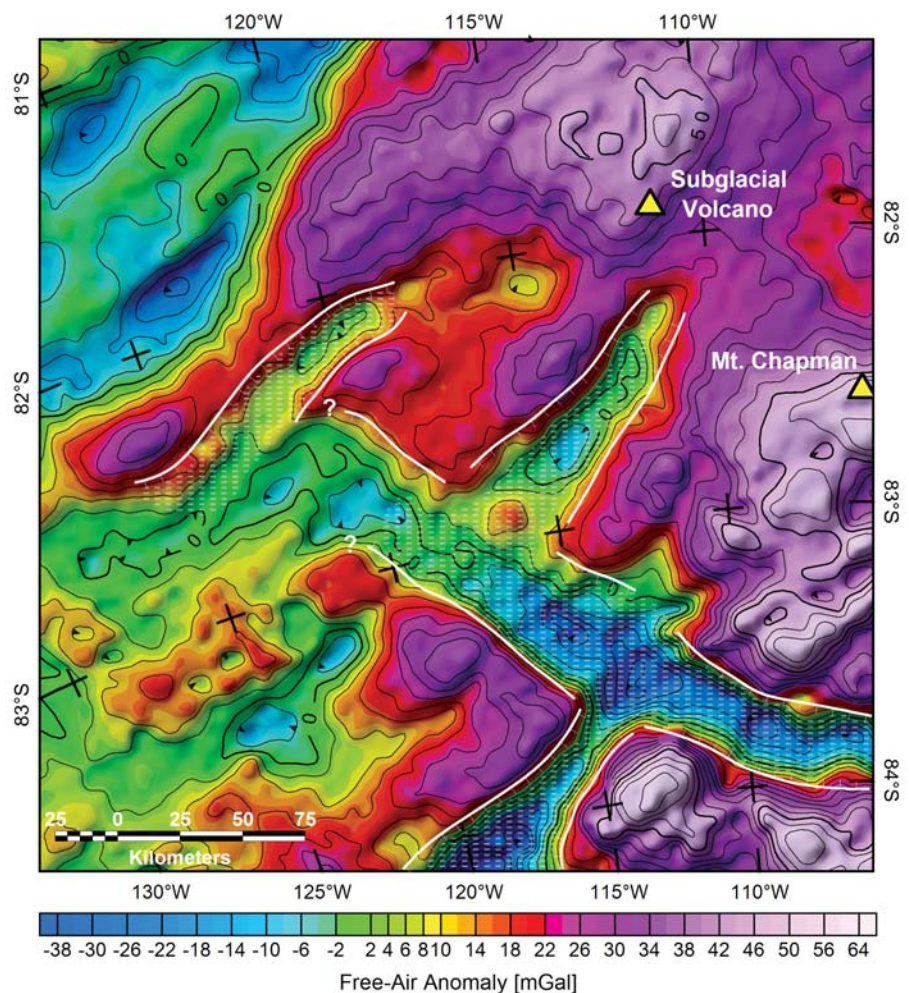
Preliminary ice-sheet modeling studies suggest the Gamburtsev Subglacial Mountains are the likely location for initiation of the EAIS and, therefore, could be a key factor

in understanding the onset of glaciation in the Paleogene. Episodic uplift of the Transantarctic Mountains throughout the Cenozoic may have influenced ice-sheet dynamics, and thus, climate. In addition, climate change may have led to increased erosion rates, accelerated uplift, and sedimentation into the Ross Sea.

What are the distribution, nature, and origin of sub-glacial lakes and what is their relation to crustal structure and heat flow?

The presence of sub-glacial lakes may have important implications for ice-sheet dynamics and for terrestrial and marine glacial environments (Figure 3). Study of the lakes pro-

Figure 2. Geologic features such as sedimentary basins and sub-glacial volcanoes are believed to exert an influence on the dynamic behavior of the overlying ice sheet. These features can be mapped using aerogeophysical data and interpretation techniques. The image shows sedimentary basins beneath fast-moving West Antarctic ice streams as interpreted from sub-glacial topography, aerogravity, and aeromagnetic data. These ice streams drain the West Antarctic Ice Sheet. It is believed that the sedimentary basins, together with sub-glacial water, provide the necessary lubricant to enable rapid basal flow within ice streams. Image courtesy of M. Studinger (LDEO) using data from the CASERTZ project.



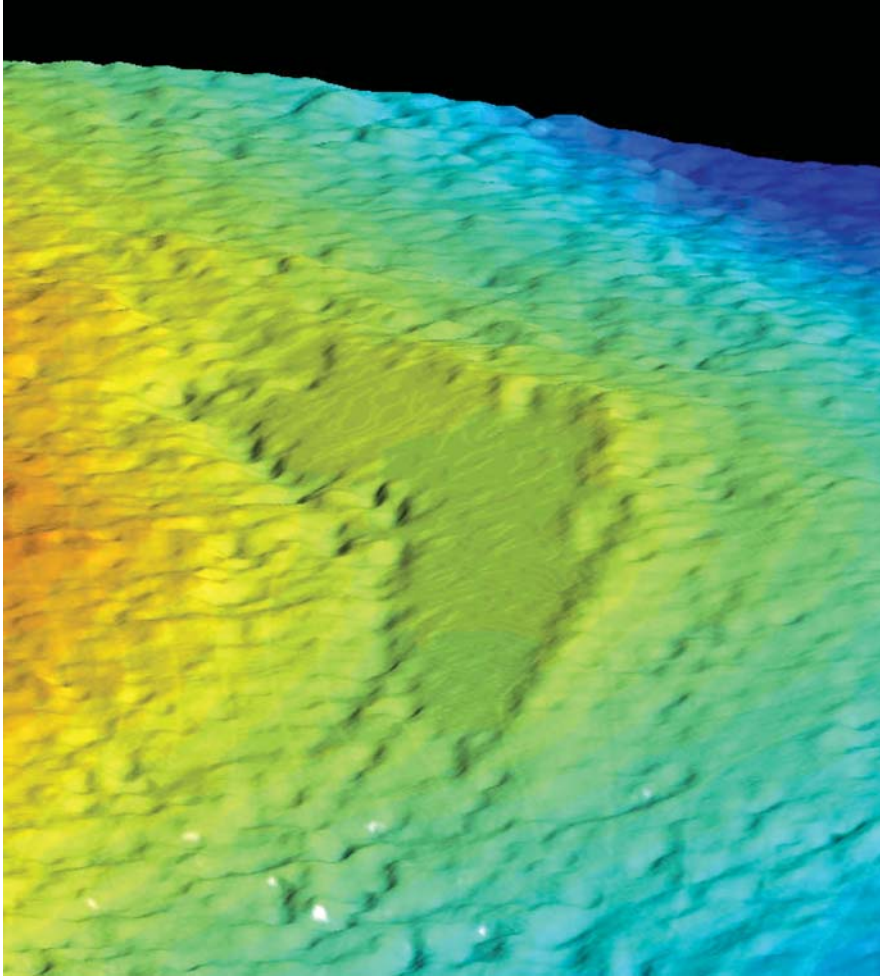


Figure 3. Buried beneath several miles of ice in Antarctica are lakes ranging in size from Lake Ontario to lakes the size of Manhattan. More than 100 lakes have been identified to date. Lake Vostok, the largest sub-glacial lake on Earth, is believed to harbor life that has been isolated from open exchange with the atmosphere for several million years. Image shows a perspective view of the ice surface above Lake Vostok compiled from ERS-1 radar altimeter data. Lake Vostok is the flat, featureless area. Image courtesy of M. Studinger (LDEO) using RAMP elevation data provided by the National Snow and Ice Data Center (NSIDC).

vides a way to understand the interaction between geologic and biologic processes. In addition, the extreme environments of these lakes may be analogous to those of the early Earth and planets, revealing the conditions under which life began (Figure 4).

#### What is the volume of the ice sheets and the range of sea-level fluctuations on different time scales?

To understand the relationship between ice mass balance and sea level, the current ice-sheet volume needs to be determined. A more accurate

estimate of the Antarctic ice-sheet volume can be used to calibrate the eustatic sea-level curve from oxygen isotope data for the present and maximum possible variations of the global sea-level curve.

#### CRUSTAL ARCHITECTURE AND EVOLUTION OF THE UNKNOWN POLAR REGIONS

Unraveling the role of Antarctica in global geodynamic processes requires a basic understanding of the poorly known East Antarctic shield and West Antarctic basement.

#### What role did East Antarctica play in Precambrian continental growth processes?

Because East Antarctica occupied a central position in early supercontinents such as Rodinia and Gondwana and may represent ~15% of Earth's Precambrian crust, it is key to understanding the processes governing continental growth spurts in the late Archean to mid-Proterozoic. Issues include the role of magmatism, accretionary tectonics, continental break-up, and subduction in early Earth history. Tectonic, erosion, subsidence,



and glacial history can be determined by knowing the age, lithology, and three-dimensional geometry of sedimentary basins in East Antarctica (Figure 5).

**What was the timing and magnitude of Mesozoic to Cenozoic extension in Antarctica, and how did it affect the global plate-motion circuit?**

Extension in the latest Mesozoic period rifted Australia and New Zealand from Antarctica. Little is known about large regions of the continental margin around the perimeter of Antarctica because sea-ice cover makes them inaccessible to ships.

Aerogeophysical surveying of remote or frequently ice-covered regions is needed to study the timing of extension, uplift, and magmatism in Antarctica. This information will help determine mechanisms of continental breakup and relative motion between East and West Antarctica. Extension rates and lithospheric thinning have a direct influence on magma-production rates and volcanism; however, the higher production rates in the late Cenozoic do not appear to be the result of higher extension rates. As for the geodynamics of rifting in an ice-covered environment, knowledge of lithosphere geodynamics in Antarctica's ice-covered environment will clarify its feedback on other global systems.

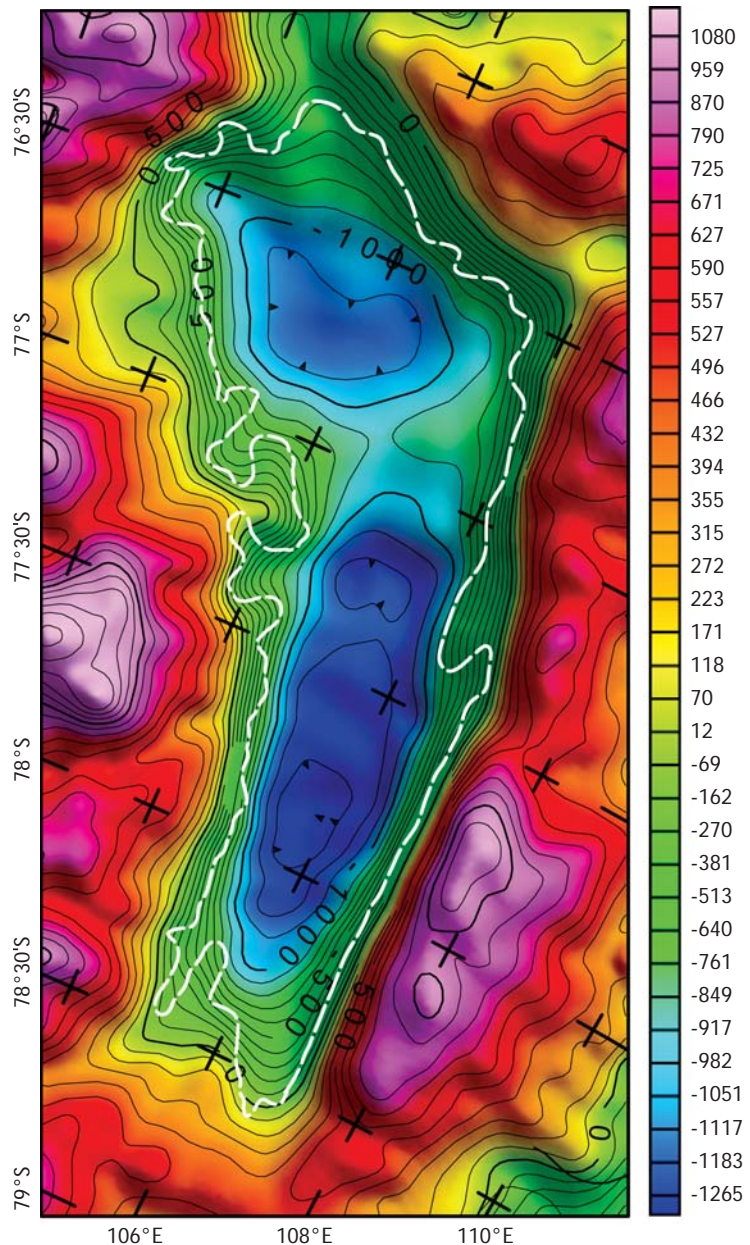


Figure 4. The sub-glacial bed is one of the most inaccessible places on Earth and it is the least studied part of Antarctica. Image shows the depth and shape of sub-glacial Lake Vostok estimated from aerogeophysical data. Lake Vostok is divided into two sub-basins that exert an important influence on water circulation within the lake. The sub-glacial hydrosphere, formed in response to the interaction between sub-glacial geology and ice dynamics, is a previously unrecognized, immense, possibly interconnected system that represents a potential habitat for life in an extreme environment. Sub-glacial environments are the closest terrestrial analogs to the icy domains on Mars or the Jovian moon Europa. Figure after Studinger et al. (2004).

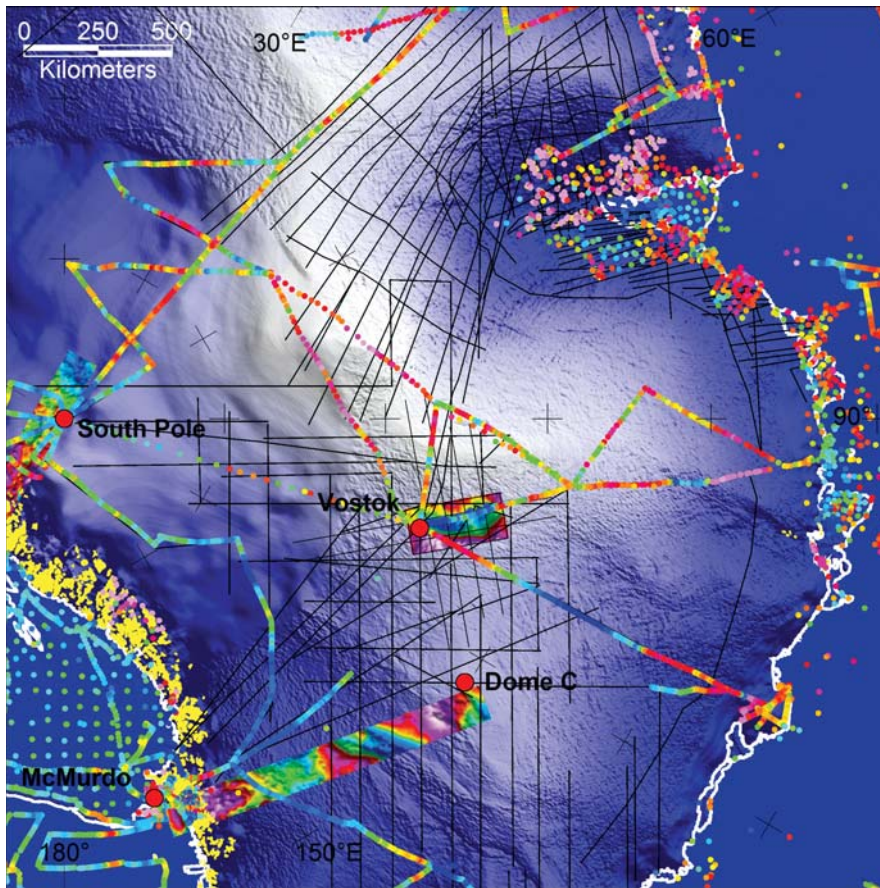


Figure 5. East Antarctica, the size of the conterminous United States, remains virtually *terra incognita* because we are unable to reach it using available aircraft. These color-shaded relief ice-surface maps were compiled from topographic data derived from satellite radar altimetry, airborne radar surveys, the Antarctic Digital Database (ADD), and RAMP elevation data provided by the National Snow and Ice Data Center (NSIDC). Colors indicate gravity data (ADGRAV Project); black lines show location of ice-thickness data. Image courtesy of M. Studinger, LDEO.

### 2.1.3. GOALS AND CONTRIBUTIONS

We seek to gain an improved understanding of the geologic and tectonic processes in polar regions, the interaction of these processes with ice-sheet dynamics and climate, and the role Antarctica plays in the global geodynamic system. Over the last few decades, research has focused on developing conceptual models for these processes. Only a significant improvement in data quality and quantity will permit us to address

the outstanding scientific questions and move towards a quantitative understanding using newly developed modeling capabilities.

#### LARA DATA SETS AND PRODUCTS

The primary product concerning Antarctic geology and geophysics will be a set of maps consisting of sub-glacial and ice-surface topography, and gravity and magnetic anomalies. These grids will form the basis for deriving a structural framework that can be interpreted in terms

of sub-glacial geology and tectonics. In particular, these data can be used to delineate the distribution and thickness of sub-glacial sedimentary basins and identify the locations of sub-glacial volcanics. Magnetic and density domains often coincide with lithotectonic domains and thus can be used to derive structural and tectonic maps in ice-covered regions. Table 2 summarizes the data sets that are necessary to answer the key questions and the data products that can be derived from these data sets.

Table 2.

FIRST-ORDER DATA PRODUCTS			
Data Set	Available?	Will LARA Provide?	Raw Data Sets Required
Ice-surface topography	North of 86°S from satellite measurements. The large footprint of radar altimeters and the sparse track spacing of the ICESat laser altimeter limit the resolution.	Yes, high-resolution (few cm) along track and from swath laser	Laser altimeter
Sub-glacial topography	West Antarctica: reconnaissance surveys East Antarctica: largely unknown	Yes, resolution depends on flight line spacing	Laser altimeter and ice-penetrating radar (depth sounder)
Gravity-anomaly maps	West Antarctica: reconnaissance surveys East Antarctica: largely unknown	Yes, resolution depends on distance to source and flight line spacing	Gravity, ice-surface elevation (from laser altimeter), and ice thickness from radar
Magnetic-anomaly maps	West Antarctica: reconnaissance surveys East Antarctica: largely unknown	Yes, resolution depends on distance to source and flight line spacing	Magnetics, ice-surface elevation, and ice thickness

DERIVED DATA PRODUCTS	
Product	Analysis Tools and Remarks
Distribution and thickness of sub-glacial sediments (including rift basins and draped deposits)	Forward and inverse modeling of gravity and sub-glacial topography data. Depth to magnetic basement estimates using deconvolution methods.
Structural mapping (trend analysis and identification of sub-glacial faults)	Delineation of characteristic magnetic and gravity domains using methods based on horizontal gradients and 3-D analytic signal. Comparison with provinces of known lithologic, metamorphic, and structural character in Antarctica and surrounding plates.
Distribution of sub-glacial volcanism and magmatism	Identification of typical patterns in magnetic and topographic data. Depth to the source estimates using inversion techniques.
Crustal thickness and mechanical parameters of the lithospheric plate	Forward and inverse modeling of gravity and sub-glacial topography data ties to crustal thickness estimates from refraction seismic studies and teleseismic receiver function analysis
Geothermal heat flow and hydrothermal bed condition	Analysis of potential field data. Estimate basal melt rates from analysis of internal layer in the ice sheet.
Basement geologic mapping of the East Antarctic shield	Interpretation of magnetic signatures, in particular, of Precambrian geologic units and magnetic and gravity mapping of arc terranes.



## THE ROLE OF LARA IN AN INTEGRATED MULTIDISCIPLINARY RESEARCH PROGRAM

Airborne geophysics is a crucial tool for an integrated multidisciplinary Antarctic geology and geophysics research program. Over the past several years, the geology and geophysics community has developed a strategy for continental exploration. This strategy has been agreed on in several NSF-funded workshops, including REVEAL, FASTDRILL, SEAP, and most recently in the workshop on Frontiers and Opportunities in Antarctic Geosciences. The strategy involves a sequence of steps, starting with regional airborne geophysical surveys to identify scientific targets in ice-covered regions. This initial step will be followed by deployment of passive seismic arrays, high-resolution airborne geophysical surveys, ground-based geophysics, and eventually drilling. Passive seismic studies, ground-based geophysics, and drilling cannot provide a regional geologic context in the ice-covered areas without regional aerogeophysical surveys.



## 2.2. GLACIOLOGY

### 2.2.1. SCOPE AND RELEVANCE

The Antarctic ice sheet is the largest ice mass on Earth. It contains about 80% of the world's freshwater supply. Covering an area of 13 million square kilometers (approximately one and a half times the size of the continental US), it contains enough ice to raise global sea level by about 65 m. Annual snowfall on the Antarctic ice sheet is equivalent to a few millimeters of sea level, thus a small imbalance between snowfall and discharge of ice and melt water into the ocean would have a significant effect on sea-level. About half of the total sea level rise, currently believed to be about 1.8 mm/year, is attributed to the melting of terrestrial ice, which includes non-polar glaciers and the Greenland and Antarctic ice sheets. Data from Antarctica, though still sparse, suggests a net loss from the WAIS equivalent to 0.2 mm/year. The EAIS is approximately in balance, but there is considerable uncertainty.

Ice sheets are dynamic systems. Their waxing and waning are controlled by a number of factors, including changes in incoming solar irradiation due to orbital variations; alterations in Earth's atmospheric composition; and interactions among the solid Earth, ice, climate, and ocean systems. Despite extensive re-

search, major questions remain unanswered. There is no consensus on whether global warming will cause the ice sheets to grow or shrink in the short term. Most scenarios predict that atmospheric warming would cause greater precipitation, resulting in initial thickening of the ice sheet. On a longer time scale, this trend may reverse because changes in ice dynamics could lead to increased discharge and grounding-line retreat. As warming reaches a threshold, surface runoff would become the dominant wastage mechanism and surficial meltwater would further increase outlet glacier discharge by lubricating the ice-sheet bed.

In the last decade, our picture of a slowly changing Antarctic ice sheet has radically changed. Observations have revealed dramatic changes in ice-stream behavior, ranging from complete shutdown of ice streams to manifold increases in velocity. In addition, iceberg calving has increased in frequency and millennia-old floating ice shelves are disintegrating (Figure 6). The recent discovery of complex flow patterns, extending deep into the interior of East Antarctica, challenges the view that the Antarctic plateau is a slow-moving, homogenous region (Figure 7). These findings inject a new and very compelling sense of urgency for gain-

ing a better understanding of the evolution of the ice sheet.

Large areas internal to East Antarctica are poorly sampled and even less well understood. Attempts at estimating its mass balance and confirming ice-sheet models are hampered by the paucity of data. Comprehensive airborne surveys of surface elevation and mass balance, bedrock lithology, and ice thickness have been restricted to a few areas, mostly in the Ross Sea sector of the WAIS and near major stations on the EAIS. Most of the key satellite missions, with the exception of RADARSAT mapping missions, do not cover the South Pole and its neighborhood. Although bed elevations have been determined in several million locations during the last half century, large regions of the EAIS bed are still unexplored (Figure 8). Due to the lack of satellite altimetry coverage around the South Pole, surface topography observations south of 86 degrees are limited to a few over-snow traverses that are less accurate than the satellite observations.

New observations from a long-range airborne platform will complement the information from satellites, existing aircraft, and field programs; will enable us to map the surface and bedrock topography, lithology, and englacial layering in unexplored

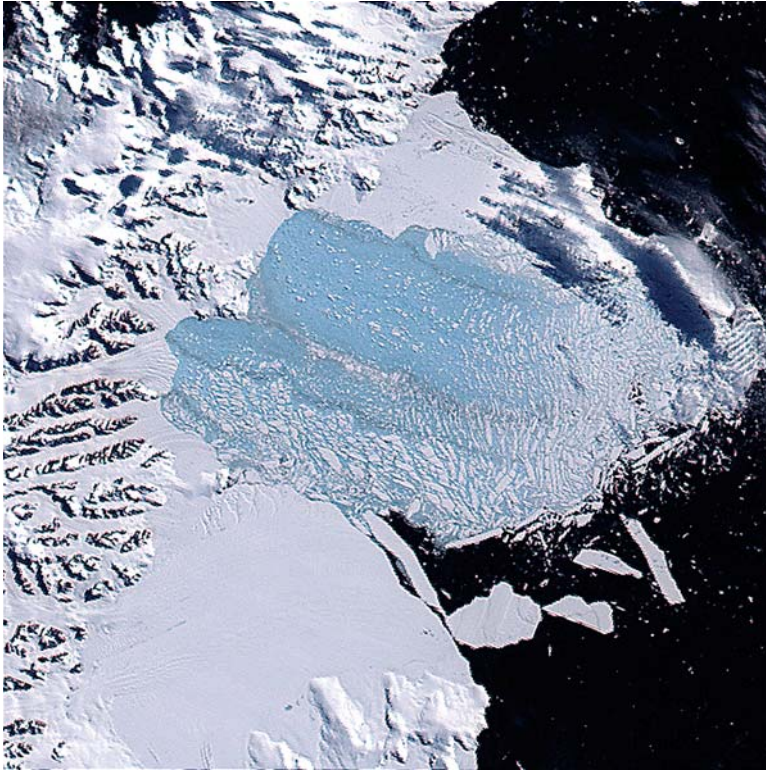


Figure 6. Beginning on 31 January 2002, a portion of the Larsen B ice shelf larger than the size of Rhode Island, disintegrated in a 35-day period. Analysis of Moderate Resolution Imaging Spectroradiometer (MODIS, image from March 7, 2002) satellite images at the University of Colorado's National Snow and Ice Data Center revealed that pools of meltwater on the surface enhanced the propagation of crevasses, destabilizing the ice shelf (after Scambos et al. [2004]). The collapse of the Larsen B ice shelf has fueled speculation regarding the impact of global warming on Antarctic ice masses. Although the validity of global change scenarios remains controversial, the Intergovernmental Panel on Climate Change (IPCC) has concluded that high-southern-latitude processes are sensitive indicators of climate change. The collapse of the Larsen B ice shelf is the largest retreat of an ice shelf on the Antarctic Peninsula over the past 30 years.

areas; and will improve our quantitative knowledge of the variability, changes, and extremes of surface, englacial, and basal processes.

### 2.2.2. KEY QUESTIONS

#### What is the relationship between climate change and the ice sheets?

Growth and shrinkage of the ice sheets are closely connected to changes in Earth's climate system. For example, a change in Earth's surface temperature either increases melting

or prolongs the period of snow persistence; however, shrinkage or expansion of ice sheets influences Earth's albedo, which changes the heat budget at the surface. Such linkage between the climate system and ice-sheet dynamics occurs over many spatial and temporal scales. While accumulation and snow-densification processes act over years to decades, the ice sheet reacts to internal and external forcing over centuries to millennia. All of these processes are recorded within the ice; some are simply waiting to be

deciphered from the internal structure of the ice sheet.

The polar regions are intimately linked to the global climate system, sea level, and marine, freshwater, and terrestrial ecosystems, and they can amplify and drive changes elsewhere in the Earth system. To understand these links, it is imperative to study the current configuration and behavior of the Antarctic ice sheet and the surrounding ice shelves. Interdisciplinary research addressing the status, changes, processes, and

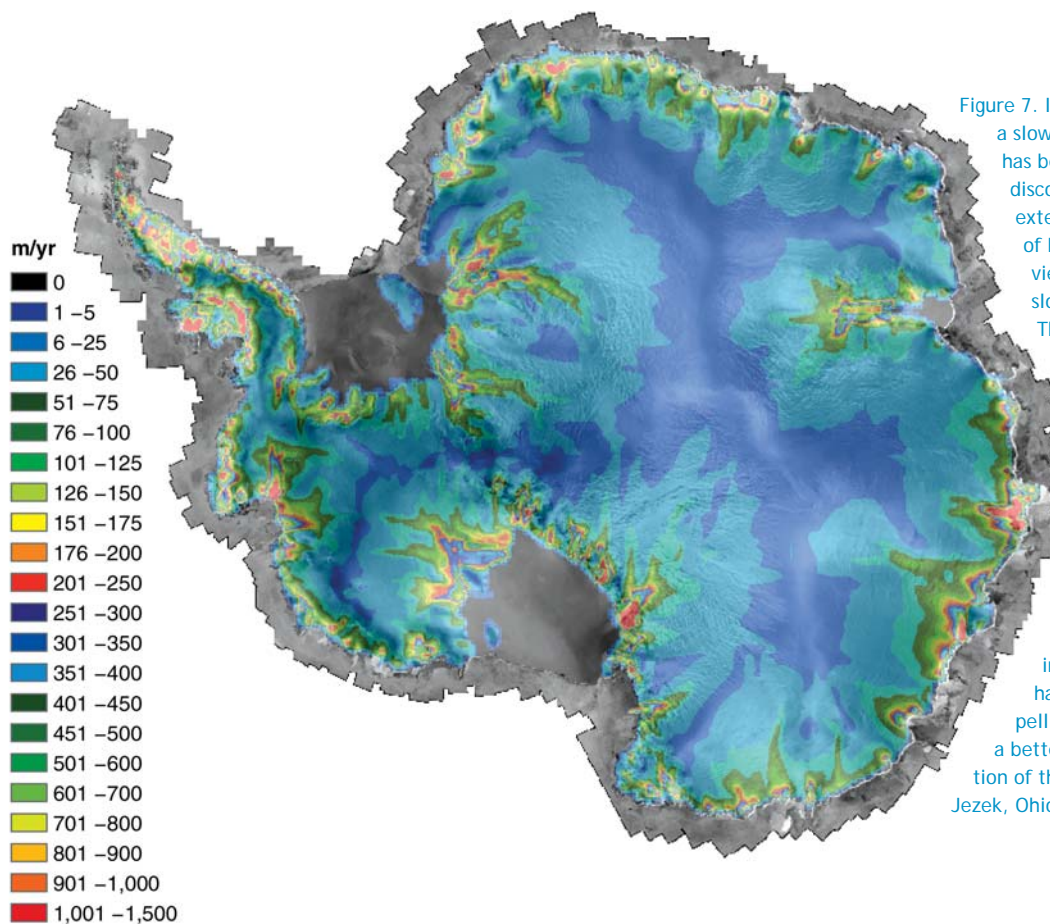


Figure 7. In the last decade, our picture of a slowly changing Antarctic ice sheet has been radically altered. The recent discovery of complex flow patterns, extending deep into the interior of East Antarctica, challenges the view that the Antarctic plateau is a slow-moving, homogenous region. The balance velocity map, shown here overlain on the RADARSAT mosaic, indicates a complex flow pattern within the interior of the Antarctic ice sheet. The existence of fast-flowing outlet glaciers, originating deep in the interior of the East Antarctic Ice Sheet, has been confirmed by the RADARSAT missions. The discovery of this complex flow pattern in the interior of the continent has injected a new and very compelling sense of urgency for gaining a better understanding of the evolution of the ice sheet. Image courtesy of K. Jezek, Ohio State University.

connections of all major Antarctic systems (ocean, sea ice, atmosphere, solid Earth, and ice sheet) by coordinated measurement campaigns and by assimilating the data into complex models is needed to better understand past ice-sheet behavior and improve prediction of changes.

#### What are the controls and interactions governing ice-sheet dynamics?

Ice-sheet dynamics are strongly influenced by the geological and topographic characteristics of the sub-

strate on which the ice sheets rest. This effect may be a missing link in understanding ice-climate interaction. For example, observations beneath the WAIS suggest that the easily erodible sedimentary bed and the availability of sub-glacial water play key roles in triggering fast ice streaming and are responsible for the presence of the fast-flowing ice streams that account for nearly all WAIS discharge. Sub-glacial water mixed with sediments reduces the resistance at the ice-sheet bed, thus allowing fast

ice motion. Therefore, the distribution of easily erodible sediments and geothermal flux within the former marine sedimentary basins of the West Antarctic rift system influences ice-flow pathways and modulates ice-stream behavior. To better understand these processes, further studies of the geologic control on ice dynamics, such as the mechanism of ice-stream onset, the interaction between accumulation and englacial processes, and the influence of basal hydrology and heat flow, are needed. By



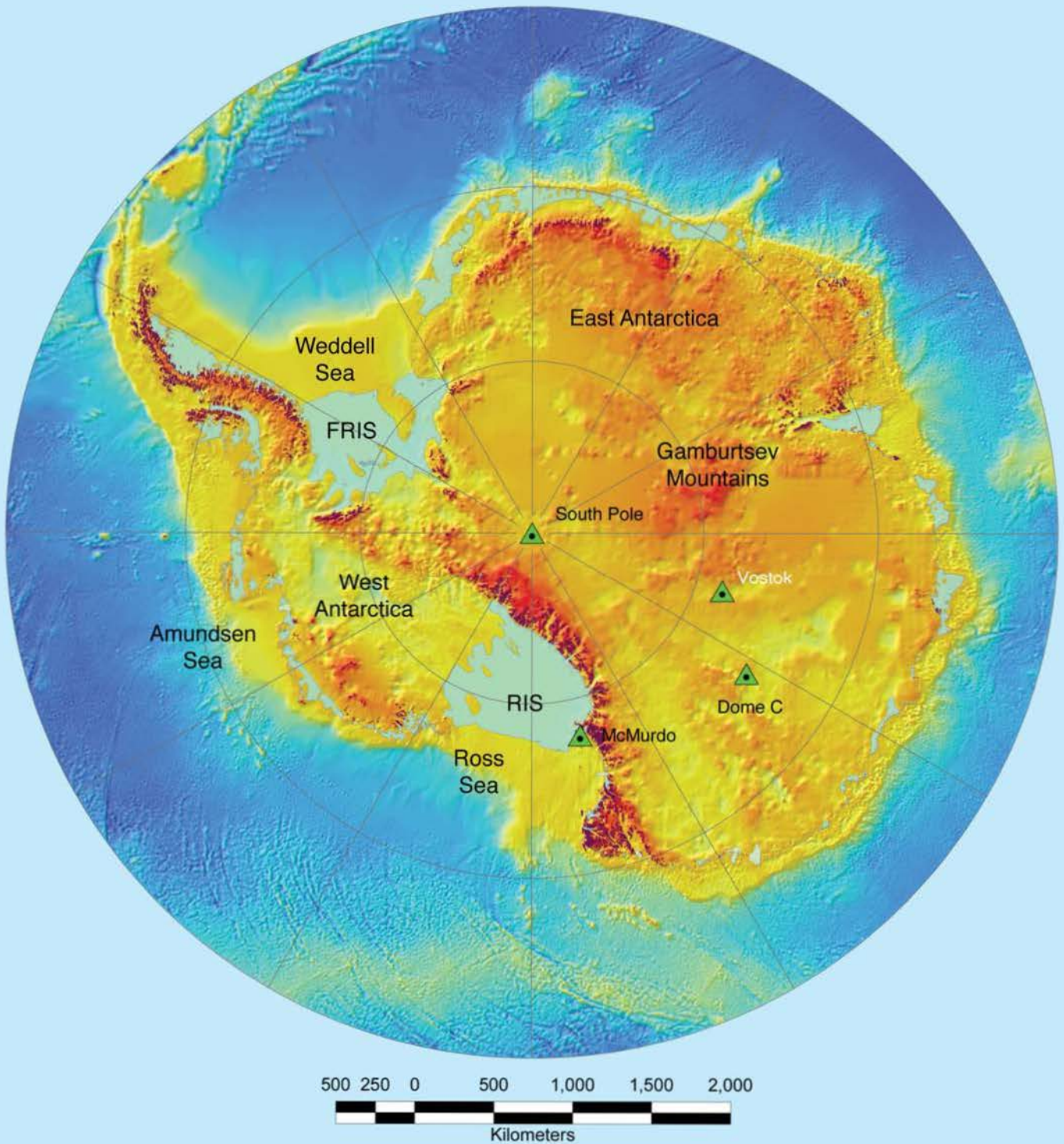


Figure 8. Sub-glacial bedrock elevation from BEDMAP compilation, showing large unexplored areas within the interior of East Antarctica (flat, featureless regions). The elevated topography of the Gamburtsev Sub-glacial Mountains in East Antarctica is thought to have been the nucleation point for the formation of continental ice sheets during the Permian-Carboniferous glaciation and the Oligocene transition from a greenhouse world to an icehouse world. Despite this crucial role in ice sheet formation, the sub-glacial topography in East Antarctica is only sparsely sampled. More detailed knowledge of the sub-glacial topography is necessary for studies of long-time ice-sheet evolution, formation of continental ice sheets, and ice-flow modeling of the dynamic behavior of ice sheets. FRIS: Filchner-Ronne Ice Shelf; RIS: Ross Ice Shelf. Data courtesy of the BEDMAP project. Image courtesy of M. Studinger, LDEO.

characterizing the underlying forcing, more realistic ice-sheet models with complex boundary conditions can be developed, resulting in better predictive capabilities. Detailed surveys of sub-glacial geomorphology permit investigation of the inception and evolution of the Antarctic ice sheet from local highland glaciations to a continental-scale ice sheet.

#### What are the distribution, nature, and interconnection of sub-glacial lakes?

In addition to Lake Vostok, which is the most prominent sub-glacial lake, over 145 sub-glacial lakes have now been identified under the Antarctic ice sheet. The large number of sub-glacial lakes suggests that the sub-glacial environment is a previously unrecognized, immense, possibly interconnected, hydrological system. The sub-glacial hydrosphere, formed in response to the interaction between sub-glacial geology and ice dynamics, represents a potential habitat for life in an extreme environment.

The sub-glacial bed is one of the most inaccessible places on Earth and it is the least-studied part of the Antarctic ice sheet. Melting of basal ice occurs where geothermal heat is trapped beneath the thick ice sheet. Following the hydrological gradient, the sub-glacial meltwater flows toward the ocean, forming a large, interconnected sub-glacial hydrological system. Although water depth usually ranges from the millimeter

to meter scale, basal water may accumulate in sub-glacial depressions, forming deeper, easily detectable sub-glacial lakes. These lakes, and the connecting sub-glacial hydrological system, provide a habitat for life. Sealed from free exchange with the atmosphere for many millions of years, sub-glacial environments are the closest terrestrial analogs to the icy domains on Mars or Europa. Understanding how tectonics, topography, and climate influence ice-sheet flow and the characteristics of a sub-glacial hydrological system that may support life is one of the most exciting challenges of polar research.

#### What are the current dynamics of coastal areas?

Recent observations revealed significant changes around the Antarctic Peninsula, including ice-shelf thinning and break-ups. These rapid changes are attributed to warming air and seawater temperatures. Although the ice stored in the Peninsula is insignificant in terms of sea-level rise, some model suggests that similar changes can occur quite rapidly over the large ice shelves of “mainland” Antarctica. Moreover, the glacier surges triggered by the disintegration of the Larsen Ice Shelf confirm the important role of the buttressing effect of ice shelves in stabilizing marine ice streams and outlet glaciers. Although the validity of global-change scenarios remains controversial, the Intergovernmental Panel on Climate

Change (IPCC) has concluded that high-southern-latitude processes are sensitive indicators of climate change. From these observations we have learned that major changes are taking place at specific locations in the Antarctic on much shorter time scales than previously anticipated. Coordinated efforts, including collection of airborne, satellite, and field observations, and modeling, are needed to study the main glaciological, meteorological, and oceanographic processes occurring in coastal areas and their interactions.

#### 2.2.3. CONTRIBUTIONS FROM LARA

A long-range research aircraft could monitor the surface processes of coastal and interior Antarctica with higher spatial resolution than that of satellite data. Moreover, an aircraft would also collect observations of englacial and sub-glacial structures and processes that are not (yet) possible from satellites.

#### STUDY OF THE INTERIOR OF ANTARCTICA

A long-range instrumented aircraft could complete the comprehensive survey of basal topography needed to provide crucial boundary conditions for ice-sheet models. An aircraft could provide more detailed surveys of areas of particular interest, such as those undergoing rapid

change. Airborne geophysical mapping (gravity, magnetics, and ice-penetrating radar) would enable us to infer the study area's basal lithology, geomorphology, thermal regime, and hydrology, and internal ice-sheet layering. Knowledge of these land and ice characteristics is needed to understand how geology controls ice-sheet evolution, and to develop and test more realistic ice-sheet models.

Laser altimetry would be the primary sensor used for topographic mapping, estimation of mass balance, and change detection (Figure 9). NASA's ICESat satellite laser-altimetry mission has proved that satellite laser measurements can provide accurate elevations for the whole ice

sheet. However, airborne laser altimetry offers more flexibility by enabling flights along flow lines or across drainage basins, thus providing more ideally distributed measurements for the ice-sheet modelers. Ice-penetrating radar observations are essential for selecting remote drilling sites and for establishing a comprehensive history of paleoclimate by correlating records from ice cores separated by several hundred kilometers (Figure 10). Internal layers may also provide information about past changes in ice dynamics by preserving relict features, such as scars and buried crevasse zones, or by depicting migrating domes or basal melt. Surface mass balance and snow accumulation

can be inferred from high-resolution, near-surface internal layers mapped by using specially designed airborne ice-penetrating radars.

Airborne digital imaging sensors, operating in different spectral domains ranging from visible to microwave, could provide useful information on ice-surface energy balance and mass balance by mapping ice surface physical conditions (extent of surface melting, grain size, exposure of old ice in ablation zone) and surface elevation changes. These sensors are also important for monitoring the changes of the outlet glaciers and ice streams and for mapping ice surface features (e.g., flow bands, crevasses, ice-stream margins) that could pro-

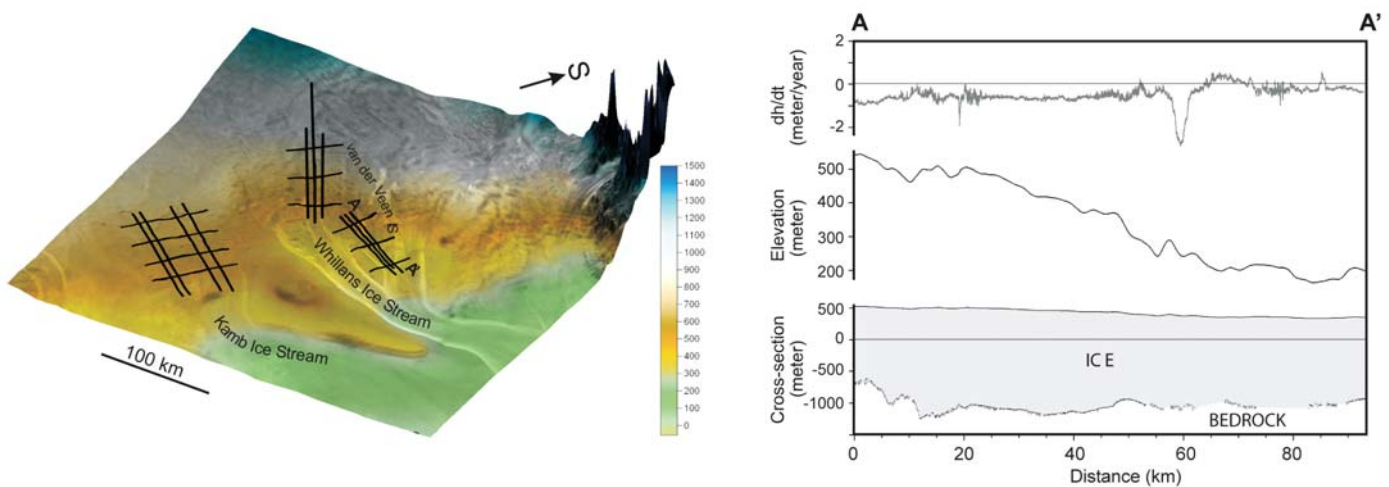


Figure 9. Repeat laser-altimeter surveys are capable of estimating surface-elevation change rates and thus changes in ice thickness and volume. Left panel: flight lines on RADARSAT mosaic draped on the color shaded using RAMP Digital Elevation Model provided by the National Snow and Ice Data Center. Right panel: repeat airborne laser altimetry along the van der Veen ice stream (AA') indicates thinning over the upstream region (data from NSF SOAR facility, figure adapted from Spikes et al. [2003]). Courtesy of Bea Csatho, BPRC.



vide clues for understanding present and past ice dynamics.

### DYNAMICS OF COASTAL AREAS AND SURVEY AROUND THE EAST ANTARCTIC ICE SHEET

Data collection required to fill crucial gaps in knowledge at the coastal areas includes: (1) ice thickness along the coast, over specific basins, and along the grounding lines of outlet glaciers and ice streams; (2) observa-

tions of ice-shelf bottom melting and its spatial and temporal variability underneath floating ice shelves; (3) repeat, stereo, multispectral digital aerial photographs to map ice velocities of outlet glaciers, ice-shelf processes and their evolutions through time, including thickness changes, tidal motion, calving, rifting, and surface melt; and (4) past extent of ice cover from glacial geomorphology over outcrops. These observations would allow study of the history of

the deglaciation, present changes in coastal region, major processes responsible for outlet glacier thinning and ice-shelf melting, and the interaction among ice-sheet, ice-shelf, and ocean systems. A long-range airborne survey, completing the observations in (1) to (4) along the entire perimeter of the EAIS or across several individual drainage basins, could also provide outgoing flux data for estimating ice sheet mass-balance changes using the volume budget approach.

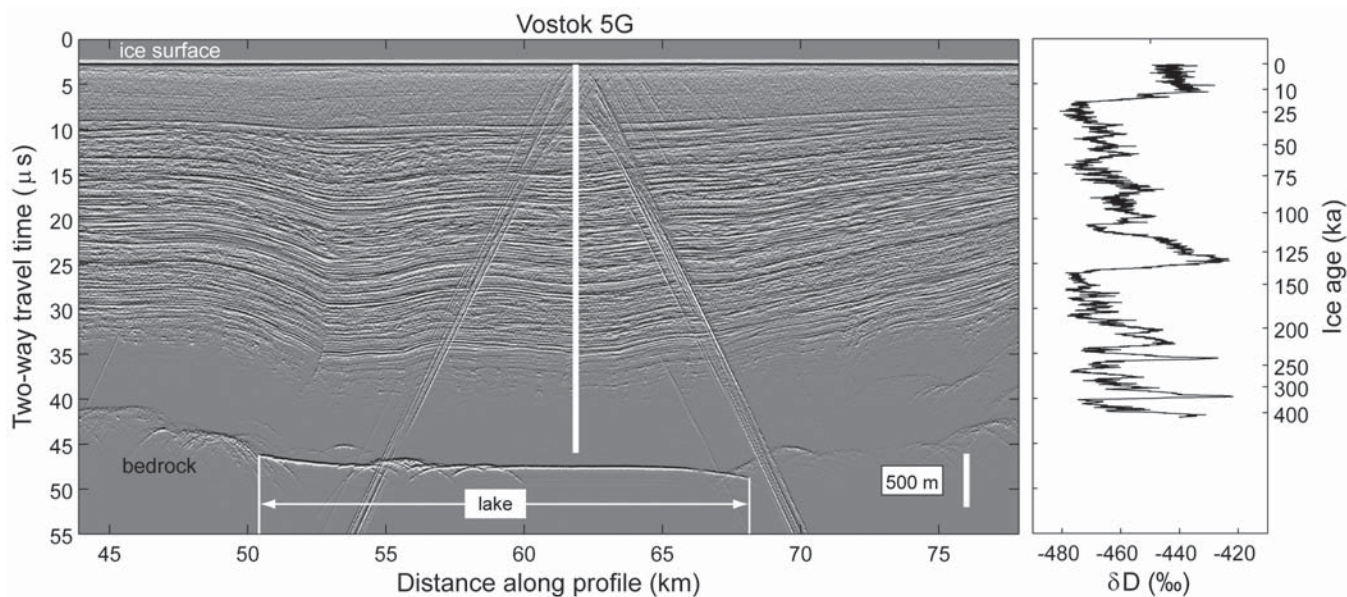


Figure 10. Vertical cross-sectional picture showing isochronous internal layers in the East Antarctic Ice Sheet over sub-glacial Lake Vostok. The image has been constructed using sequential records of ice-penetrating radar data that are reflected back to the surface. The internal layers are the rugged, near horizontal features in the upper two-thirds of the image. These layers result from the changing conductivity associated with periods of increased precipitation of volcanic dust and represent time horizons. Lake Vostok is the smooth, strong reflector between 45 and 50  $\mu$ s two-way travel time. By linking the internal layers within the ice sheet to age-depth relationships determined from the Vostok 5G ice core, the dynamic history of the ice sheet can be revealed. Courtesy of M. Studinger (LDEO) using data from the NSF SOAR facility and Petit et al. (1999) provided by the National Snow and Ice Data Center.

## EXPLORATION OF SUB-GLACIAL HIGHLANDS

Climate models suggest that the high elevation of Antarctic mountains, for example, the Gamburtsev Subglacial Mountains in East Antarctica, were crucial in localizing the first Cenozoic ice sheet. Sub-glacial geomorphology records the key processes of ice-sheet inception and evolution. Airborne geophysical surveys will provide sub-glacial topography and other important boundary conditions, such as bedrock lithology and physical properties of the ice-bed interface, for coupled climate-ice models.

## OTHER SUGGESTED GLACIOLOGICAL APPLICATIONS

The instrumented long-range aircraft could also: (1) monitor the most dynamic components of the ice sheet, such as selected sites at the WAIS, Weddell Sea, Amundsen Sea, Ross Sea, or Lambert glacier; (2) map blue-ice locations, perform meteorite reconnaissance, and investigate meteorite-concentration mechanisms; (3) calibrate and validate satellite measurements to improve models for conversion of raw satellite measurements into geophysical parameters; and (4) conduct systematic airborne gravity and magnetic surveys to improve knowledge of Earth's gravity and magnetic fields.

## 2.3. OCEANOGRAPHY

### 2.3.1. SCOPE AND RELEVANCE

The southernmost part of the world ocean, south of the Antarctic Circumpolar Current (ACC) and with a seasonally varying, highly mobile sea-ice cover, is referred to as the “Antarctic Zone.” This zone encompasses a number of individually named seas, two of which—the Weddell and Ross Seas—occupy basin-scale indentations in the continental margins. Processes occurring in the Antarctic Zone are crucial in a global-ocean context, as it is here where upper-ocean cooling and ice formation lead to deep convection and formation of dense Antarctic Bottom Water that is found throughout most of the temperate ocean and contributes to the global meridional overturning circulation (MOC) (Figure 11). The southernmost Weddell and Ross Seas, locations where the great continental ice sheets impinge on the coastal ocean, are primary formation sites for dense, deep bottom water. Intensive studies of these regions have provided detailed qualitative and quantitative information on bottom-water formation, its dynamics, and controlling mechanisms. Other regions around the periphery of Antarctica also play significant roles.

Oceanographic research is carried out in the Antarctic Zone using data from surface vessels and satellites in

conjunction with numerical models. Vessels allow observation of subsurface ocean processes and detailed measurement of ice characteristics. They are essential to understanding the ocean and the accompanying processes that interact with and impact the overlying sea ice. Satellites are useful in studying large-scale sea-ice processes and have been invaluable in documenting interannual changes that reflect global-scale oceanic and atmospheric interactions between the Antarctic and lower-latitude oceans. Aircraft use, in an Antarctic Zone context, is almost always limited to measurements obtained from helicopters that use vessels for their bases of operations. Wide-scale airborne operations have not been used for study of the Southern Ocean.

Focal points for oceanographic research in the Antarctic Zone relate strongly to ice-ocean interactions and their relationship to the deep-ocean circulation and to atmosphere-ocean fluxes of heat and momentum. The region is biologically rich, and numerous studies focus on understanding regional marine ecosystems and their coupling with the physical system. Significant efforts have addressed the physical, chemical, and biological coupling of the Antarctic Zone with more temperate oceans, and these efforts have tended to focus on climate-change issues.

In the Antarctic Zone, oceanographers seek to quantify and understand the physical mechanisms that couple freshwater output (icebergs and sub-glacial runoff) from the Antarctic continent to deep-water formation, sea-ice cover, and the large-scale wind field. These mechanisms change continuously on time scales from interannual, to seasonal, to several days (synoptic meteorological processes), to less than a day (tidal and inertial phenomena). Of most concern are interannual changes in freshwater output that might be linked to climate changes.

The ocean’s physical system contains feedback loops at different spatial scales. At the largest scales, these loops couple with climate-change processes (Figure 12). The Antarctic Zone plays a leading role in the global climate system, in large part because of the sea-ice cover and its impact on energy balance through its high albedo and control over atmosphere-ocean energy fluxes. Its ecosystems harbor a rich and diverse biota ranging from plankton to seabirds and large marine mammals. These ecosystems fluctuate in response to physical processes and, in turn, impact the carbon balance for the entire Southern Ocean. In sum, the Antarctic Zone is a physically energetic and biologically active region that is strongly coupled to climate

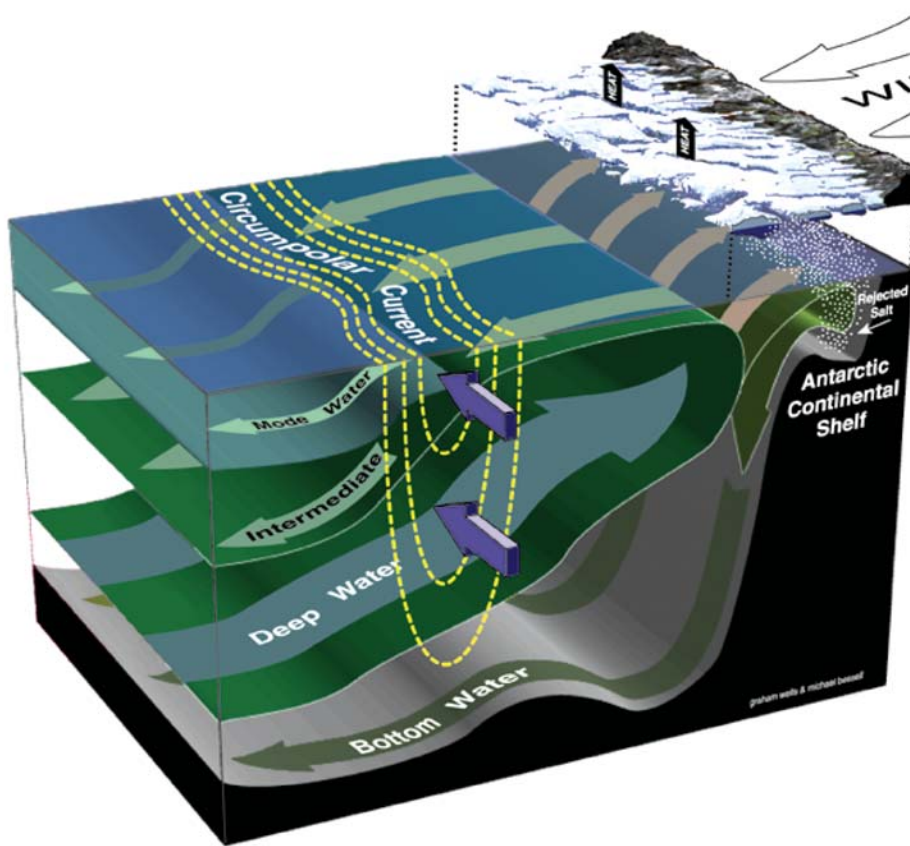


Figure 11: Schematic cross-section of the Southern Ocean, illustrating the two overturning cells that contribute to the meridional overturning circulation (MOC). The MOC is responsible in large part for circulation and renewal of deep water throughout the global ocean. The deeper of the cells, marked by sinking and northward flow of bottom water from the Antarctic continental shelf, depends upon surface water freezing on the shelf, which then releases salt into the underlying water and increases its density to the point where it sinks. This process depends on low air temperatures and southerly winds, and is strongly impacted by the concentration of sea ice over the continental shelf. Wind fields, air temperatures, and sea-ice concentration are all subject to interannual variability and may be impacted by climate change. Image courtesy of S. Rintoul, CSIRO.

changes and that impacts physical and biological processes over much of the world ocean. A full understanding of the region is essential to our ability to predict events related to global climate change.

### 2.3.2. KEY QUESTIONS

Although we understand conceptually many of the crucial processes and interactions in the ocean's Antarctic Zone, we lack quantitative information related to many such processes. Much of our information is spatially and temporally discontinuous because it has been collected

from various platforms under the auspices of projects having varying objectives, and at different times and locations. The more nearly instantaneous large-scale coverage available from satellites lacks the resolution needed to quantitatively assess many important processes, and is unable to see beneath the sea surface. The key questions that we would hope to address using a long-range research aircraft derive in part from the shortcomings in existing data and in part from the knowledge that significant processes occur at many temporal and spatial scales and are coupled over great distances such that they

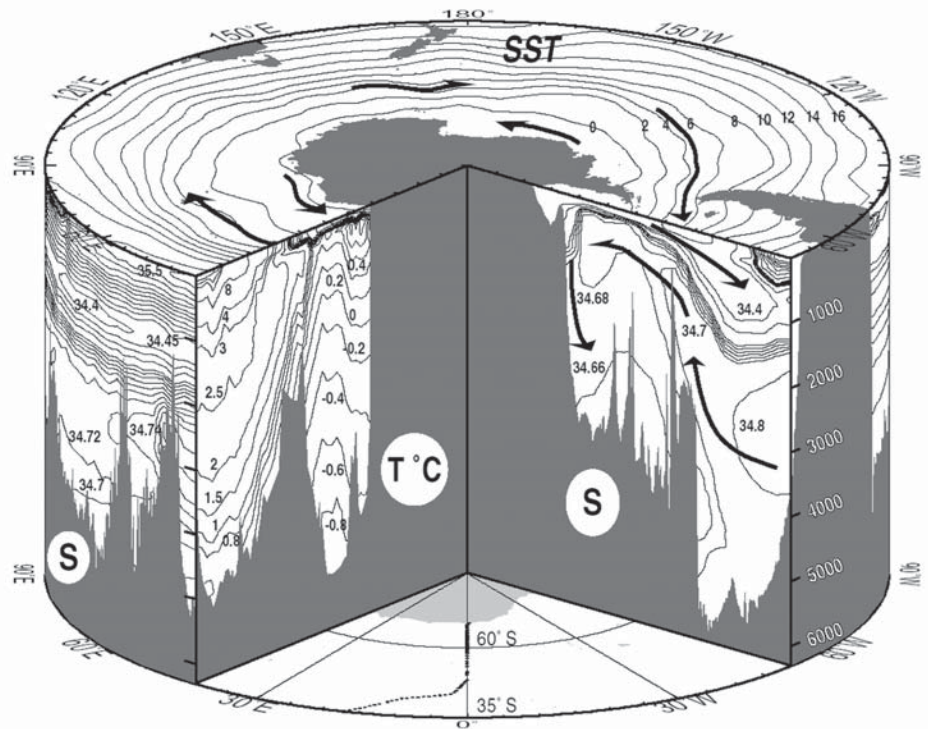
are difficult to sample from slow-moving surface vessels. Further, some critical processes are event-driven and require the ability to very quickly deploy an observational platform. The following are some key questions related to phenomena that we know or expect are important but for which we lack information adequate for understanding or quantification.

**What is the interannual variation in sea-ice thickness on a basin-wide scale?**

The Arctic Ocean ice pack is decreasing in thickness and areal extent. The



Figure 12. Isotherms of the annual sea surface temperature (SST) in °C, salinity S in PSU and ocean temperature (T) in °C around Antarctica. Bold arrows show the mean large-scale ocean circulation and emphasize the Antarctic Circumpolar Current flowing clockwise around the continent, the counterclockwise coastal current system that surrounds much of the continent, and the subsurface overturning cells referenced in Figure 11. The coastal current is a consequence of regional winds and local freshwater budgets and is, like the deep overturning cells, subject to modification by climate change. Figure from Gordon (1999).



Antarctic ice pack does not appear to be decreasing in extent, but we have few data from which to assess trends in thickness.

#### What role does water densification in polynyas and beneath ice shelves play in the global ocean meridional overturning circulation?

Much of the water densification that drives the global ocean MOC occurs in small, nearshore, ice-free areas called polynyas and in the ocean cavities beneath the seaward extensions of the great Antarctic ice shelves. We are attempting now to sample beneath the ice shelves using autono-

mous underwater vehicles (AUVs); however, we have been unable to sample in detail the winter polynyas because they are inaccessible when active for either seagoing vessels or short-range aircraft. Our understanding of these key features remains conceptual rather than quantitative and is based largely on numerical model results and satellite observations rather than detailed, *in situ* field measurements.

#### How does deep-ocean water temperature vary over interannual scales?

Deep-ocean water temperatures in the Antarctic Zone can vary over in-

terannual time scales, for example, the ongoing basin-wide warming in the deep Weddell Sea. This warming appears to be a rebound from massive cooling associated with a mid-ocean polynya that occurred in the mid to late 1970s. Quantitative verification of the cooling mechanism requires direct observation of such an event, should it occur again, and subsequent monitoring of deep-ocean temperatures over a large area. Surface vessels make poor platforms for the rapid response needed to observe a transient and unpredictable cooling event in the remote central portion of a deep ocean basin.

Over what distances does sea ice drift in the Antarctic Zone from the time it forms to when it fully melts?

Knowledge of ice drift over broad regions and over decades is essential to our overall understanding of the ice response to climate change. Large-scale movement of sea ice in the Antarctic Zone has been observed using satellite-tracked drift buoys deployed irregularly over time and at different locations over several years, often in association with specific research projects such as the highly successful Arctic Data Buoy Program that has been in place since about 1980. Buoy data have shown that the annual sea-ice cover forms near the continent, is driven north by the wind, then melts where it meets the warmer waters of the Antarctic Circumpolar Current. At present, available buoy data are inadequate for us to quantitatively assess interannual changes in these drift patterns, or the ensuing ice balance, that relate to changes in the forcing wind field.

Efforts to establish a regular and reasonably dense network of drift buoys in the Antarctic Zone have generally fallen short for a number of reasons. A significant obstacle has been the lack of available ships or aircraft from which to deploy buoys. A long-range aircraft to aid in buoy deployment would help to significantly advance the science.

What role do marginal ice zones play in the Antarctic Zone's physical and biological activity?

Transition regions, such as the marginal ice zones and the boundaries between ice sheets, or shore-fast ice and the ocean, tend to be sites of intense physical and biological activity that are not quantitatively well understood. Significant events in such regions are strongly forced by local meteorology and tend to be event-driven. Focused shipboard projects have provided detailed information on pertinent processes at specific locations and during some seasons. Our field-based information is, however, insufficient to understand interannual variability or to predict the impact of climatic variations on these systems.

### 2.3.3. GOALS AND IMPACTS OF A LONG-RANGE RESEARCH AIRCRAFT

Availability of a long-range research aircraft would advance ocean research in the Antarctic in two ways. First, it would provide a new facility uniquely capable of gathering data over a very broad area, with a much higher resolution than available from satellites, and would allow deployment of air-dropped, remote instruments. Second, it would allow collection of data in a rapid-response mode, permitting investigation of processes at work in event-driven phenomena such as polynyas or ice-shelf breakup.

The examples given in this report illustrate scientific problems whose quantitative solutions require field-data acquisition and data-driven modeling efforts. The problems are diverse; however, their solutions can all be greatly facilitated by a platform capable of sampling at high resolution over large distances. Most needs can be met using a long-range aircraft suitably equipped with surface-sensing instruments, shallow penetration systems such as active microwaves, and air-droppable buoys and probes. Such a platform can carry out, for example, rapid cross-basin traverses to obtain information on the sea-ice cover to a high level of detail impossible to obtain in any other way. Satellite-tracked drift buoys might be dropped at points along the flight track, allowing tracking of ice movement for as much as a year following the flight. Such transects could be continued annually, or even more frequently, for a decade, providing a wealth of information on pack-ice characteristics and movement. This information would be invaluable in assessing the interactions of the pack-ice cover with other large-scale systems in a climate-change context.

The subsurface ocean is of equal import, and an aircraft might, during a cross-basin transect, drop ocean probes such as expendable CTD (conductivity, temperature, and depth) profilers to obtain a “snapshot” of the upper ocean that interacts directly with the ice cover. Acoustic probes



are under development that would allow interrogation, from an aircraft, of deep sensors such as might be used to measure interannual change in deep-ocean properties. The deep sensors may have been deployed during austral summer from surface vessels; if a suitable aircraft is available, it is technically feasible to deploy such a system, albeit perhaps of limited scope, through an open lead from an aircraft during a winter transect.

An ability to reach remote sites quickly and on short notice in order to carry out rapid and detailed process observations, such as those related to discrete events, is likewise needed. In the case of a wintertime coastal polynya, for example, a suitably instrumented aircraft could fly from the sea ice across the polynya and over the ice shelf, recording winds, ice conditions, heat fluxes, and ocean-surface wave conditions while dropping probes to measure subsurface ocean structure. Such features are generally inaccessible to surface vessels because they are surrounded by heavy pack ice.

As noted above, transition zones such as the marginal ice zone are often regions of energetic, concentrated physical and biological activity. Overflights from an instrumented aircraft could provide basic information on sea ice, wind, and sea-state conditions as well as surface color information tied to upper ocean biota. Although the same information can be (and has been) obtained us-

ing a surface vessel, acquisition of repeat transects through a given area in order to understand interannual variability are generally not feasible from a ship. It is even possible that such transects could be obtained on a routine basis, at little cost, using an aircraft transiting from a base station to the Antarctic across the marginal ice zone and pack ice to the south.

At present, we have insufficient information on interannual change in these complex systems on which to base an understanding.

Significant changes can come about in a physical system due to short-period, high-energy events such as severe storms. Surface vessels can observe these effects if they happen to be at the right spot when a storm strikes, but are too slow, and also very likely to be committed elsewhere, to feasibly investigate such events. Under ideal conditions, an aircraft could, however, be at the site of an event within a day to provide detailed information on weather conditions. Given that severe storms can be predicted at many locations surrounding Antarctica, an aircraft could be used to survey a site of particular interest both prior to and following a storm. Such information will be crucial in assessing that portion of climate-change impacts related to changing storm frequency and intensity.

Finally, long-range aircraft can be used in conjunction with surface vessels and satellites. The aircraft would provide data beyond the geographi-

cal range accessible to the vessel and at higher resolution than available from the satellite. Effectively, aircraft would fill in the data-collection gap at the intermediate scale between shipboard programs that collect high-resolution data in relatively small regions and satellites that collect low-resolution data over broad swaths.

## 2.4. ANTARCTIC ATMOSPHERIC SCIENCE

### 2.4.1. SCOPE AND RELEVANCE

The Antarctic atmosphere plays an essential role in global climate, and can be considered a “test tube” for meteorological processes as proposed by H.H. Lettau nearly 40 years ago. More recently, the Intergovernmental Panel on Climate Change has concluded that high-southern-latitude processes are sensitive indicators of climate change. The Antarctic continent is of particular importance in global-change scenarios because of its large continental ice sheets; if these ice sheets fully melted, sea level would rise 65 m, flooding coastal communities. Most recently, attention has focused on the collapse of the Larsen B ice shelf (Figure 6), fueling speculation that global warming may already be impacting Antarctic ice masses. Significant teleconnections between Antarctica and the tropical latitudes have been identified on a number of times scales and need to be understood before realistic studies of longer-term global-change issues can be conducted.

By mid-latitude standards, the Antarctic atmosphere remains poorly sampled. There exist only a dozen upper-air stations to monitor the wind and temperature fields throughout the troposphere and lower stratosphere, and only South Pole station

is available to routinely measure the upper-air environment over the interior of Antarctica. The atmosphere over the oceanic region to the north of Antarctica is the largest data void on the planet. Conventional station data have been supplemented significantly by observations from automatic weather stations (AWS) since about 1980. Currently, some 100 AWS exist over Antarctica that provide much-needed data at the surface. An enhanced array of satellite-borne sensors will become available in the next few years. Integration of the impressive stream of data collected by the next-generation sensors will require ground-truth measurements that are currently not available.

One component that still needs to be added to the observational strategy is a dedicated, instrumented airborne platform. This platform would enable measurements of atmospheric components and processes that are currently not possible. Examples include the vertical structure of wind, temperature, and pressure associated with topographically induced circulations or mesoscale cyclones; sampling of tropospheric chemical constituents and chemical processes; and cloud microphysical properties. In addition to providing a basic understanding of the Antarctic atmosphere, these measurements are

needed to enable development of atmospheric and chemical models. For example, mesoscale weather-prediction models containing elaborate and comprehensive physical representations of the atmosphere and underlying surfaces are available to the scientific community for a wide variety of numerical experiments, but have not had the detailed validation required to advance the skill of atmospheric simulations.

To conduct any of these atmospheric studies, the airborne platform must support a payload sufficiently large to carry the required instrumentation and must have long-range capability to reach critical sites over the broad Antarctic continent.

Antarctic atmospheric studies are at an important crossroads. Nearly 50 years ago the International Geophysical Year (IGY) commenced with the promise “...to observe geophysical phenomena and to secure data from all parts of the world; to conduct this effort on a coordinated basis by fields, and in space and time, so that results could be collated in a meaningful manner.” A primary emphasis was placed on the polar regions that previously had been studied in a piecemeal fashion. Confronted with unparalleled issues of global change, scientists are now challenged to renew the IGY promise.

## 2.4.2. KEY QUESTIONS

How are Antarctic atmospheric processes linked to the rest of the global atmosphere?

Climate phenomena in Antarctica are represented by variations that cover a wide range of spatial and temporal scales. The range of variability of, for example, atmospheric circulations, cloud cover, and precipitation, is not well known for Antarctica because of limited analysis and uncertainties in new data sources. Airborne measurements of local and regional circulation systems will enable direct assessment of the transport processes at work between high southern latitudes and the rest of the globe. This knowledge is required to understand and model climate variability and change, such as that associated with the El Niño Southern Oscillation (Figure 13), which is concentrated in the South Pacific sector of Antarctica and is poorly understood.

What role does the Antarctic atmospheric heat sink play in global climate?

The higher latitudes of the Southern Hemisphere, including the ice sheet and the surrounding sea-ice zone, are one of the two primary areas on Earth where there is net loss of energy from the atmosphere to free space.

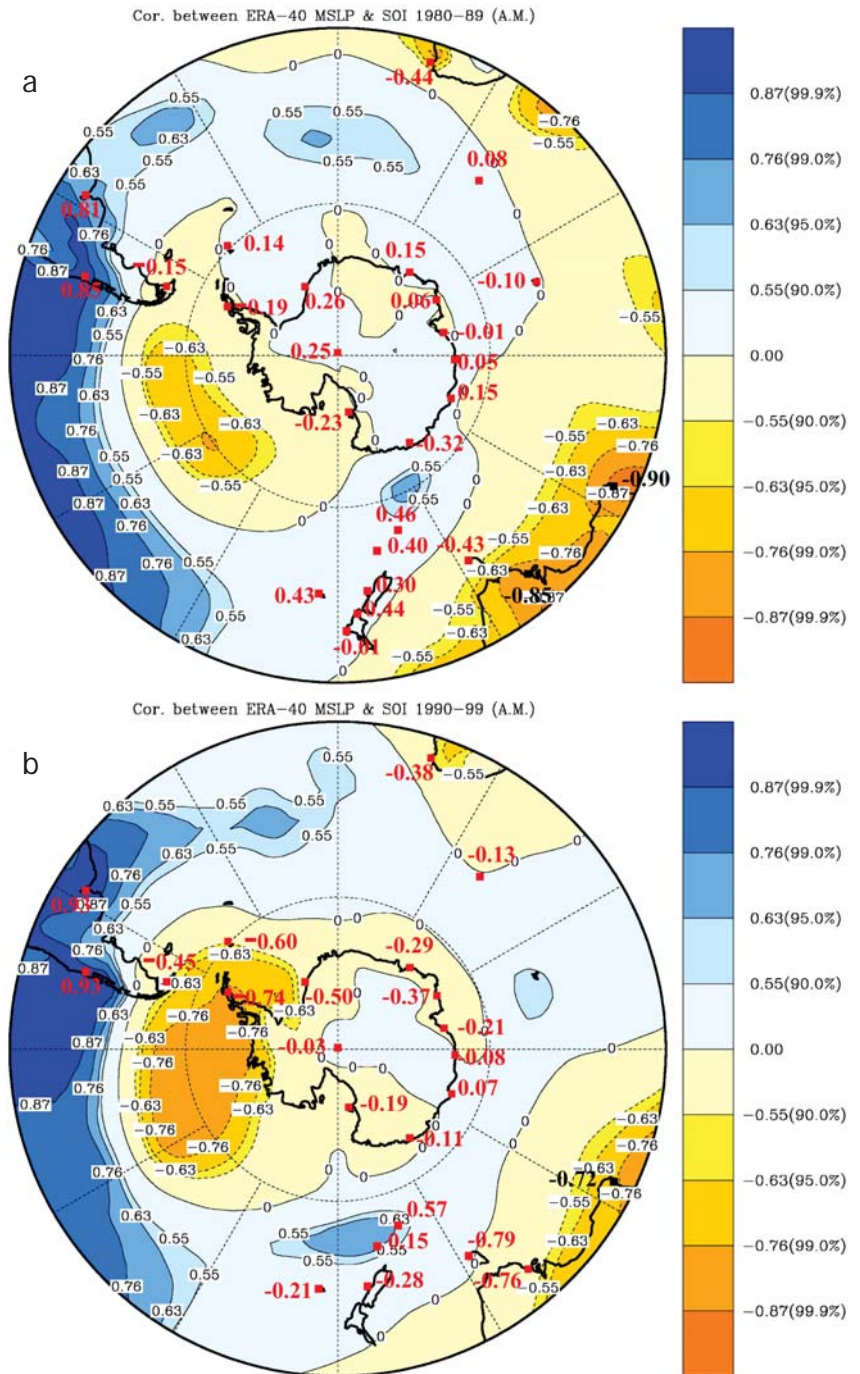


Figure 13. Annual (May–April) ERA-40 mean sea level pressure (MSLP) correlations with the Southern Oscillation Index (SOI) for (a) 1980s and (b) 1990s. Also plotted are the SOI correlations with MSLP station observations (in red) south of 30°S to validate the ERA-40 reanalysis. Significance values of the correlations are given next to the color key. The decadal variability of the El Niño Southern Oscillation teleconnection is apparent between the 1980s and 1990s as the 1990s teleconnection is more significantly marked over a larger area of the South Pacific. Figure after Fogt and Bromwich (2005).

The temperature contrast between Antarctica and the equatorial regions modulates the westerlies over the Southern Ocean. Recent studies with global climate models (GCM) have suggested that the hemispheric and global atmospheric circulations are sensitive to modest changes in the clouds over Antarctica. The extent, phase, and properties of clouds are poorly known for Antarctica. Airborne studies with advanced cloud microphysical sensors will be required before an assessment of the role of clouds can be made. Sampling of the Antarctic clouds requires airborne measurements in meteorological conditions where alternate landing sites are especially important. Presently, ski-equipped, long-range aircraft offer the best capability to perform this function.

#### How does the mountainous topography of Antarctica impact the global atmospheric circulation?

The Antarctic terrain is the single-most dominant factor in shaping the meteorology over the ice sheet and oceanic regions adjacent to the continent. The broad, high-ice topography is an effective barrier to air masses impinging on the continent from the north. Physical characteristics of the ice sheet are responsible for the radiative budget near the surface and serve to strongly constrain the dynamics of the Antarctic atmosphere. Although we know that south polar

geography is the antithesis of that displayed by the north polar basin and is responsible for the much more extreme climatic conditions displayed by the atmosphere surrounding Antarctica, a detailed understanding of the terrain impacts on atmospheric circulation is still lacking. Airborne measurements will enable the strong control of topography to be documented that can, in turn, be used to assist in refinement of numerical models of the terrain-induced atmospheric flows (Figure 14). These measurements require airborne sampling over a wide geographic area.

#### What role do the Antarctic ice sheets play in global sea-level variability?

The Antarctic ice sheets store the equivalent of 65 m of global sea level. Whether these ice masses are gaining or losing water to the global ocean is very uncertain. Major glacier wastage is now being observed along the Antarctic Peninsula and in the Pine Island Bay region. This could be offset by contemporary precipitation increases over the continent as a whole, as suggested by atmospheric reanalyses and glaciological accumulation measurements. Precipitation estimates from atmospheric models are likely to provide the definitive description of Antarctic precipitation trends since the IGY, but the results depend on cloud and precipitation parameterizations that need detailed

testing. A well-instrumented long-range research aircraft is needed to provide the necessary measurements of the atmospheric hydrologic cycle over the full range of Antarctic environments: offshore, the coastal escarpment, the intermediate slopes, and the high interior.

#### What is the nature of air-sea interactions over the Southern Ocean?

The radiative budget of the high southern latitudes is strongly influenced by surface conditions; approximately 80% of the incoming solar radiation that hits the permanent ice sheet is reflected back to space. Sea ice is also critical to the radiation budget. Sea-ice cover varies greatly during the year, but covers a maximum surface area during September. At that time, the areal extent of the sea-ice cover is larger than the area of the continental ice sheet, thereby effectively doubling the continental area. Sea-ice extent is considered a sensitive indicator of global change. The reflectivity of the entire Southern Hemisphere is sensitive to the area of sea-ice cover; the reflectivity is actually higher during summer than winter.

Heat and moisture exchange between the ocean and atmosphere is strongly modulated by sea-ice coverage and thickness, and modulates the precipitation over the continental ice sheet. The momentum exchange between the low-level winds and ocean



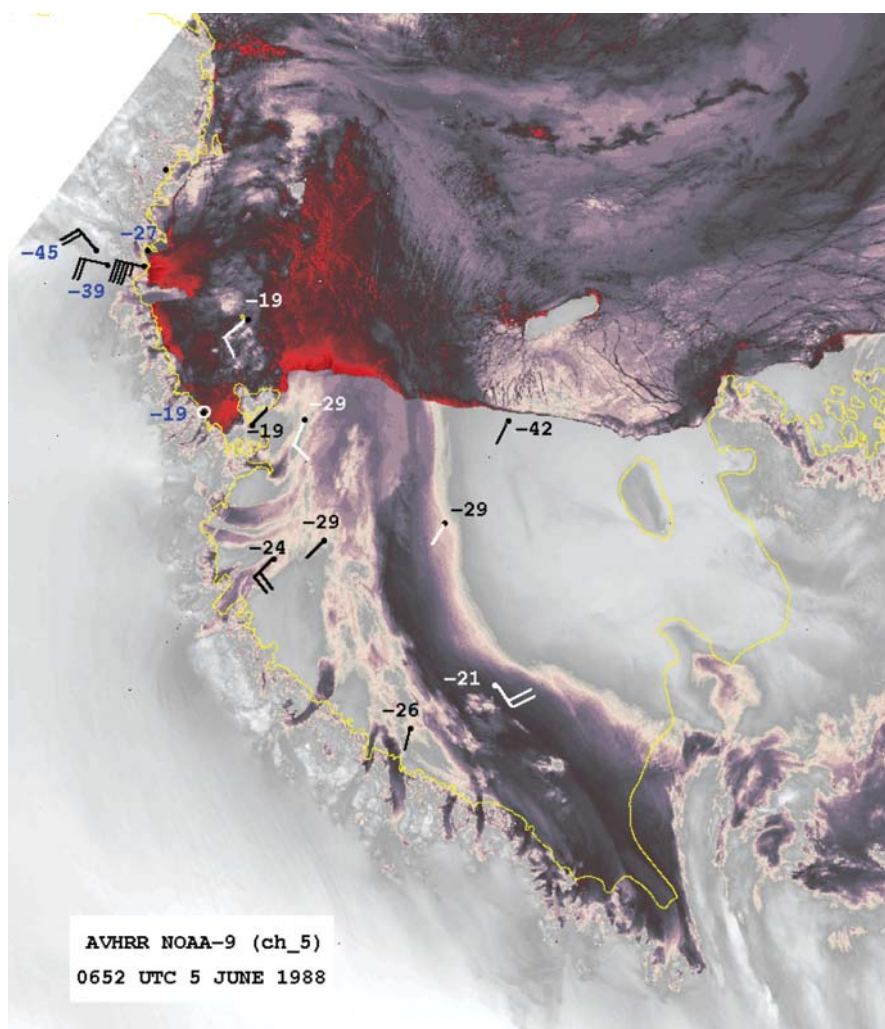


Figure 14. Thermal infrared satellite image of a topographically generated air stream from West Antarctica blowing across the Ross Ice Shelf (dark/warm feature in center, now called the RAS) in the middle of winter. Simultaneous, automatic weather-station observations of air temperature (numbers in °C), wind direction, and wind speed are plotted. Figure courtesy of D. Bromwich, Ohio State University.

is important in the northward transport of ice, development of new ice, and the local energy exchanges at the air-sea interface. The near-coastal ice generation and brine rejection contribute to the formation of Antarctic Bottom Water, the densest water in the global ocean, which couples Antarctica to the rest of the planet over the thousand-year time scale. Yet, all of these ocean-atmosphere interactions are not well understood. Airborne studies will enable fluxes of heat and momentum to be evaluated at pivotal open-ocean regimes such

as polynyas where direct interaction between atmosphere and ocean is present. Many of these regions cannot be reached with present aircraft operating in Antarctica.

#### How is the chemistry of the high southern latitudes tied to Antarctic atmospheric circulation?

The unique and largely unexplored chemistry of the Antarctic troposphere needs to be understood sufficiently to estimate chemical lifetimes, to predict product speciation and distribution, and to quantify the in-

fluence of gas-particle and gas-snow surface interactions. Knowledge of this same chemistry will also provide critical insight into the atmospheric factors that influence the levels and distributions of climate proxy species in Antarctic ice cores such as sulfate, methane sulfonate, and nitrate. In addition to enhancing chemical insights, the measurement of oxidation rates in conjunction with those of reactive and passive chemical tracers will provide a new mechanism by which air mass and chemical transport into and over the Antarctic

continent can be quantified. Of particular importance in Antarctic atmospheric chemistry is the understanding of stratospheric ozone depletion and how it impacts global climate. Airborne measurement programs can be conducted to document particular chemical pathways evident at high southern latitudes. The instruments required to measure the chemical species of interest require a heavy-lift aircraft; sampling areas of interest require a long-range aircraft.

#### 2.4.3. THE WAY FORWARD

Antarctica is a critical component of the global climate picture, yet the capability to collect fundamental atmospheric data for studying the role of the high southern latitudes in global climate is lacking. Many primary physical processes that take place in the Antarctic atmosphere have never been investigated. A fundamental requirement for such studies will be the availability of a dedicated long-range, heavy-lift airborne platform. Airborne platforms have demonstrated their capabilities in middle-latitude studies over the past four decades and continue to serve as key observational tools in process studies. The Antarctic environment is a far more hostile, remote, and challenging frontier to conduct airborne studies and thus demands an airborne platform suited to the requirements of the polar atmosphere.

Requirements of an airborne platform include the capability for long-duration flights at levels from the boundary layer to close to the tropopause. Measurement of atmospheric state variables (temperature, pressure, winds, and atmospheric moisture), turbulent fluxes, cloud microphysical parameters, and radiative fluxes will be required. For upper-troposphere flights, extensive use of dropsondes to monitor the atmospheric structure below flight level will be necessary. Coordination of the airborne missions with ground-based observations will provide the spatial context and representative picture that is not available from other approaches. Such observations will permit a refinement of physical parameterizations within models to more properly portray the physics of the Antarctic boundary layer and the characteristics of clouds. Efforts can also be made to coordinate airborne missions with satellite overflights as a means of validating satellite algorithms for retrieval of, for example, cloud properties and precipitation. Accurate, continent-wide climatological fields can then be derived from satellite data, permitting more detailed studies of the impact of the primary modes of atmospheric variability on Antarctica.

Much of the above discussion detailing requirements of atmospheric studies and aircraft requirements stems from organizational meetings of Antarctic atmospheric scien-

tists over the past five years. At such meetings, a proposal was developed to conduct the largest Antarctic atmospheric field program to date. The fundamental goal of the study, known as the Antarctic Regional Interactions Meteorology Experiment (RIME, see <http://polarmet.mps.ohio-state.edu/RIME-01/RIME.html>), is to explore in detail the atmospheric processes over Antarctica and their interactions with lower latitudes via the Ross Sea sector. The RIME scientists' universally accepted prerequisite for the study is a dedicated, state-of-the-art, ski-equipped airborne measurement platform. It is anticipated that future field project planning efforts will result in similar conclusions regarding the critical importance of an airborne platform to sample atmospheric events over a wide range of temporal and spatial scales.

## 2.5. SYNERGIES: CLIMATE-LEVEL INTERACTIONS

### 2.5.1. SCOPE AND RELEVANCE

Climate is the integrated outcome of the interaction of the physical systems consisting of the atmosphere, ocean, cryosphere, and lithosphere. It is necessary to understand the exchanges of energy among the various climate components before prediction of global change is possible. Enhanced understanding requires extensive interdisciplinary programs to enable linkages among the physical systems to be identified. The atmosphere and the ocean interact continuously over a broad range of temporal and spatial scales. The ice shelves marking the seaward edges of the Antarctic ice sheet participate in these interactions. The ice sheet responds to the underlying geology, which determines the flow patterns and the rates at which the glacial ice approaches the coastal ocean. The time scales intrinsic to the ocean, atmosphere, ice cap, and underlying earth vary greatly. Interactions that are significant climatologically span these scales. Any approach for observing systems within a global or climatological context must sample rapidly enough to include the daily to weekly time scales of the atmospheric and oceanic processes while at the same time having sufficiently

broad spatial coverage to allow assessment of the contributing geological and ice-sheet features.

Interdisciplinary studies using a long-range instrumented aircraft are inherently relevant to climate science, especially for the Antarctic, because many of the key relationships that define the present-day climate are poorly understood. Interactions among the atmosphere, ocean, sea ice, and continental ice both impact and are influenced by changes in global climate.

### 2.5.2. KEY QUESTIONS

We have a physically based, conceptual understanding of many of the interactions that significantly impact climate and the Antarctic environment. Our observationally based knowledge is, however, inadequate in many areas to quantify the interactions among components of the climate system, or to predict impacts. The related questions can be as complex as the climate-level interactions themselves. The following questions stand out among a very large number of related issues.

**How does the snow and ice budget of the continental ice sheet respond to large-scale perturbations in atmospheric parameters such as temperature and precipitation?**

Long-term stability of the ice sheets requires a balance of glacial ice loss, either as icebergs or as freshwater runoff, against input as snowfall. Vast amounts of freshwater are sequestered in the ice sheet. Changes in the freshwater balance will release water to the ocean or remove it from the ocean to add to the ice mass. The more likely scenario, in view of current global warming, would be for release of water to the ocean with a consequent sea-level rise. A broad spectrum of interactive processes needs to be quantified and understood before we can accurately predict ice-sheet behavior. At a minimum, we need to address precipitation-related phenomena, including microstructure physical processes of clouds that control precipitation nucleation, the larger-scale synoptic setting as reflected in storm behavior, and modulations of these processes by orography. Flights on the order of 1000 km will be needed to capture the fields of motion associated with cyclones. Glaciological studies must determine how a specific precipitation event is recorded in the ice sheet. Airborne surveys of snow accumulation are needed to understand the responses of the ice sheets to precipitation.

What is the interannual to decadal variability in glacial and coastal ocean processes that control formation of dense water?

Key sites for formation of the dense water that contributes to the global ocean MOC are present in the southern Weddell and Ross Seas and at other sites around Antarctica. Dense water is also formed in sub-ice cavities underlying the seaward extensions of ice sheets, particularly in the southwestern Weddell and Ross Seas. The MOC is strongly impacted by ice-sheet movements and by atmospheric and sea-ice conditions in the coastal oceans surrounding Antarctica. Although these processes have been modeled and are physically understood, we lack the observational basis to quantify or to predict interannual or decadal changes in Antarctica. Airborne surveys, capable of rapid response to discrete events and of rapid sampling over synoptic scales, can help quantify our understanding of the forcing and evolution of dense water in coastal areas. Such surveys can also help clarify feedback mechanisms among winds, open-water areas, and cyclonic storms. These airborne surveys can provide quantitative information on rates of ice production and removal, brine rejection from newly formed sea ice, and dense water formation.

How are the Antarctic climate and the El Niño Southern Oscillation linked, and how might this link impact Antarctic climate and sea ice?

ENSO is a coupled ocean-atmosphere phenomenon that, while most pronounced in tropical and subtropical Pacific Ocean, has clear teleconnections to the Antarctic where it is a significant source of variability on interannual and climatic time scales. These linkages have been detected in the Antarctic atmosphere, in sea ice fluctuations, and in ice cores. We anticipate that global warming will bring alterations in the frequency and intensity of ENSO events and in their global teleconnections with regions such as the Antarctic. The precise mechanisms through which ENSO impacts Antarctica, both the ice sheet and offshore air-ice-ocean interactions, remain controversial. Airborne observations can provide observations of coupled atmosphere, ocean, and sea-ice processes in the Antarctic centers of action for ENSO that are essential to understanding the mechanisms linking the Antarctic climate to lower latitudes.

### 2.5.3. IMPACTS OF A LONG-RANGE RESEARCH AIRCRAFT

Perhaps more than the disciplinary issues, scientists studying these interdisciplinary climatic problems can benefit greatly through observations made from a long-range aircraft. Because these problems involve processes spanning a wide range of spatial and temporal scales, many past observations have been limited in their ability to define the scales most important to interactions. For example, short-range aircraft surveys from a remote station can define continental ice properties over the range of their survey area, but cannot obtain near-simultaneous observations of conditions over a continent-wide area more appropriate to assess ice-atmosphere interactions. An ocean surface vessel is capable of detailed observations over only a small region relative to the vast Southern Ocean that surrounds the continent. An instrumented, long-range aircraft capable of landing at sites other than prepared runways can observe many of the pertinent processes over broad enough areas to provide information that is more statistically meaningful, and perhaps more relevant from a climatological viewpoint, than can be



acquired through other means. Such a platform is also capable of obtaining these geographically broad data sets over short enough time scales to comprise a “snapshot” that can be fruitfully compared with other snapshots obtained during different years, seasons, and weather patterns.

In a broad sense, a long-range aircraft is a tool for observing processes that occupy temporal and spatial scales too fine to be resolved from satellite-borne sensors and too large to be reasonably observed using platforms having limited mobility or range. Such observations would allow, from the viewpoint of a small-scale process study, extrapolation of results over a broader area. For an observational program of continental or ocean-basin scale, these observations would allow interpolation between the smallest and largest scales. There is no other facility that can reasonably play this role. The most compelling use for such a platform would be observations of the atmosphere, ice, ocean, and solid Earth related to climate change over the many temporal and spatial scales over which we expect to see climatological interactions.

# 3. Critical Research Capabilities and Needs

To pursue key goals in Antarctic science, it is necessary to acquire a geographically diverse set of fundamental observations at high spatial and (often) temporal resolution. We currently lack the data sets to build a comprehensive picture of the Antarctic environment because of a long-standing gap in our airborne capabilities. Unmanned aerial vehicles (UAVs) have been considered to fill the gap between satellite measurements and instruments deployed from field camps, seagoing vessels, and small aircraft; however, the available capabilities of UAVs are insufficient to address key scientific questions identified at the workshop. Civilian access is in a developmental state and the very limited payload of available UAVs, their mission profiles, and their operational limitations prevent them from being used in an efficient way for most Antarctic research aviation applications. Workshop participants representing the geology, geophysics, glaciology, atmospheric, and oceanographic communities thus concluded that a multidisciplinary, instrumented, long-range research aircraft is needed to provide continent-wide surveying capability. Data collected by the large variety of sensors will form the basis for a new quantitative description of the dynamic processes that form the present-day polar environment.

## 3.1. OPERATIONAL PLATFORM REQUIREMENTS

The target areas are widespread and extend over both continental and oceanic regions. To address each key question or science discipline, different survey designs and sensor configurations are required. The solid Earth, glaciology, atmospheric, and oceanographic communities represented at the workshop defined five mission profiles to address research and operational issues. This list is not comprehensive, but covers generic mission scenarios for each discipline that are necessary to achieve the vast majority of the scientific goals.

- Regional aerogeophysical mapping (gravity, magnetics, laser, ice-penetrating radar) of large (>1000 x 1000 km) areas in the deep interior of the continent on an orthogonal grid of flight lines.
- Continuous mapping of sea ice (laser altimeter, ice-penetrating active microwave, high-resolution visual band) along cross-basin transects over the Ross Sea, Weddell Sea, and from the Antarctic Convergence to the continent, with the capability to drop drifting buoys onto the pack ice.
- Regional-scale measurements of atmospheric state variables (temperature, pressure, winds, atmospheric moisture), cloud microphysics, radiative fluxes, and turbulent fluxes in an area from the South Pole to approximately 65°S. Extensive use of dropsondes to monitor the atmospheric structure below flight level.
- In-transit measurements of *in situ* atmospheric chemistry plus up- and down-looking LIDAR measurements between South Pole and coastal sites and also into deep interior of the continent.
- Localized aerogeophysical mapping (laser, ice-penetrating radar) of outlet glaciers, and grounding lines around the perimeter of the entire Antarctic continent.

Details of specific requirements for each mission profile are given in Appendix 4. Common to all mission profiles is the need for an aircraft capable of carrying an integrated payload of remote sensing and *in situ* sensors over long-distances. Almost all mission profiles require data acquisition in remote regions more than a thousand nautical miles away from existing landing sites for wheeled aircraft in Antarctica. To get to the target area and be able to survey for several hours requires a flight endurance of at least 10 hours or the capability to refuel at remote locations. In addition, the research goals outlined in this report require flights that maintain altitudes from a few hundred meters to at least 7 km. Some of the airborne mission profiles (solid Earth) require slow operational speeds for measurements, which suggest the use of a slower aircraft, such as a turboprop.

Atmospheric chemistry and physics research requires a heavy aircraft with long-range endurance, and significant load-carrying capability. The payload requirements range from 2,500 lbs for solid Earth and glaciology missions to 12,000 lbs for atmospheric chemistry missions. The number of mission scientists necessary to operate the equipment on the aircraft ranges from 3 to 16. There was a brief discussion during the workshop about what type of aircraft could potentially meet these requirements. Platforms that have

been discussed include ski-equipped LC-130s, a wheeled P-3 Orion, and a ski-equipped Basler BT-67. The key issue seemed to be whether existing wheeled aircraft would satisfy the operational requirements outlined in the mission profiles above.

The optimum scenario would be to have a variety of platforms available for use by the Antarctic scientific community. If only a single long-range research aircraft were available, an LC-130 could accomplish the broadest spectrum of scientific goals identified at the workshop, providing the best combination of endurance, payload, altitude, speed ranges, and power supply that is needed for all mission scenarios (Figure 15). A cost-effective use of an airborne research platform might be achieved through

cooperation among the various scientific disciplines and by combining missions or piggy-backing some instruments onto other experiments.

### 3.2. AIRBORNE INSTRUMENTATION

#### A. STANDARD

There was general agreement at the workshop that a basic instrument suite should be operated on each survey flight, independent of the scientific objective, and that these data should be archived and made publicly available. Capturing a core data set was seen as a cost-efficient way to improve the extremely poor data coverage of the Antarctic continent. The list of basic measurements in Table 3

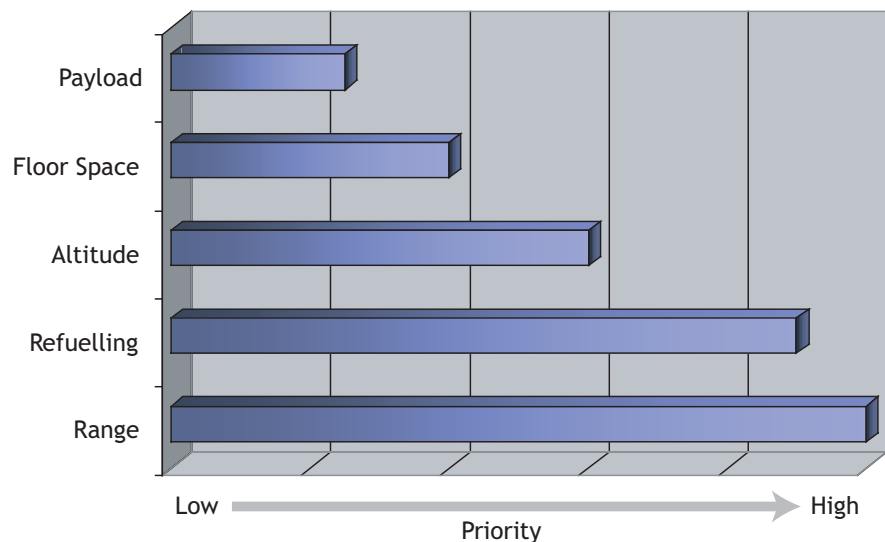


Figure 15. Aircraft requirements identified and prioritized from the scientific missions.

includes only instruments that can be operated in a semi-automated way, without additional support from equipment operators.

## B. EXPERIMENT OR DISCIPLINE-SPECIFIC MEASUREMENTS

Many of the instruments for discipline-specific measurements are available within the community and have already been used on a variety of research aircraft. The current lack of an airborne research platform,

modified to accommodate the instruments, is the main reason why these existing sensors cannot be deployed in Antarctica. For the solid Earth and glaciology communities, with the exception of the near-surface accumulation radar that is currently being developed at the University of Kansas, all sensors exist within the community. The accumulation radar is planned to be operational and available by the time a long-range research platform exists. Sensors required for oceanography also exist

except for a new multiband microwave sensor that is being developed and requires an open rear cargo door for operation. Atmospheric sensors are all flown on the NSF/NCAR C-130Q and other aircraft. Table 4 provides a list of examples of currently available, discipline-specific sensors that are known to be needed for Antarctic studies. Also included in Table 4 are the special requirements that must be met in order to install them on a research aircraft. This list is not meant to be exhaustive, as other instruments, including ones currently under development, would likely be added to this list for many discipline-specific studies.

An Antarctic research aviation facility should have the greatest possible flexibility. In addition to providing the list of measurements in Table 4, individual investigators should be able to test new sensors.

Table 3.

Basic Instrument Suite: Sensors that will be flown on the aircraft for each research flight	Geophysics & Geology	Glaciology	Atmospheric Sciences	Oceanography
Positioning: Time, inertial reference system, GPS, flight data recorder	x	x	x	x
Altitude above ground/water from laser/radar altimeter	x	x	x	x
Atmospheric state variables (temperature, pressure, moisture, winds)		x	x	x
Basic cloud parameters		x	x	x
Digital photography (not mapping)	x	x	x	x
Surface temperature		x	x	x
Atmospheric chemistry (ozone, water)			x	
Ice-penetrating radar (if small and automated operation)	x	x		x
Magnetometer (only if automated operation is possible)	x	x		

## 3.3. ANTICIPATED AIRCRAFT MODIFICATIONS AND REQUIREMENTS

To accommodate the wide spectrum of instrumentation listed in Table 4, any existing aircraft would have to be extensively modified. In preparation for this LARA workshop, in December 2003, a small group of scientists, broadly representing the solid Earth, glaciology, oceanography, and atmospheric science communities, visited the Research Aviation Facility (RAF) of the National Center for



Atmospheric Research (NCAR). The objective of this visit was to estimate the scope of modifications required for the production of a NSF LC-130 aircraft with research capabilities. RAF engineers shared their experience with the group of scientists. The assessment was done for the specific case of an LC-130, but the challenges will be similar for other types of aircraft. The scope of modifications will not only depend on the type of aircraft, but also on a particular configuration of a candidate aircraft. The following sections summarize the discussions from the NCAR site visit. The full report can be accessed on the workshop website (<http://polarmet.mps.ohio-state.edu/lara>).

**Fuselage Apertures.** Numerous sensors require penetrations in the fuselage for viewports and for air sampling, such as laser altimeters, digital aerial cameras, and many atmospheric sensors. The NSF/NCAR C-130Q aircraft for atmospheric research has 11 large fuselage apertures. Any long-range research platform for Antarctic atmospheric sciences will probably require a similar number of ports. RAF has experience with the design and installation of large fuselage apertures on C-130s.

**External Structures.** A number of instruments require external mounting on the fuselage. Examples include antenna structures for ice-penetrating radar mounted under the wings, wingtip pylons for atmospheric sciences, wing pods and magnetometers

mounted on non-magnetic stingers, or booms on the wing tips. Most externally mounted sensors require data and power cabling from the sensor to the main cabin.

**Power Requirements.** Most of the measurements and sensors require a stable power supply. Aerogeophysical and glaciological missions are on the low end and require less than 10 kVA. Atmospheric chemistry missions represent the upper end, with power requirements up to 40 kVA.

### 3.4. FACILITY MANAGEMENT AND STRUCTURE

The workshop agenda included a brief discussion on the structure of a possible Antarctic research aviation facility. The series of presentations was intended to start a discussion among the workshop participants and within the Antarctic scientific community on issues related to facility structure. This initial discussion will have to be followed by a detailed planning workshop that produces an implementation plan for a research aviation facility. Two end-member models for a facility were considered: (1) the facility provides the platform and basic data sets that are needed for each scientific discipline or mission and (2) the facility operates the platform, provides a comprehensive set of measurements as needed; maintains and calibrates all necessary

sensors; and reduces, archives, and disseminates the acquired data.

The multidisciplinary nature of the LARA platform will require a unique and comprehensive data management plan. This plan, which should be developed as a part of the LARA implementation plan, should include: (1) metadata guidelines for all LARA data sets, including calibration parameters; (2) appropriate data format specifications (e.g., NetCDF and ASCII); (3) plans and procedures for providing archival and community-wide access to data; (4) data policy guidelines; (5) procedures for collecting and processing data; and (6) a list of real-time data needs (e.g., for instrument control or flight operations).

Because of the operational complexity involved in operating a heavy aircraft with a large number of sensors and measurements, workshop participants agreed that a central management group is necessary to successfully run such a facility. Participants generally agreed on a preliminary list of sensors that should be operated by such a facility (Table 3). In addition to operating and maintaining these sensors, the facility should allow individual investigators to operate their own equipment on the aircraft.

Among the issues that have to be discussed in a future workshop are the allocation of scientific missions through a competitive process, and scientific and technical oversight of the facility. Because extensive modi-

Table 4. Currently available discipline-specific sensors and mounting need.

	Measurement or Sensor	Comments/Requirements
Aerogeophysics	Multi-frequency, ice-penetrating radar, including deep radar sounder and an accumulation radar	Externally mounted antenna structures require wing attachment points and cables within the wing structure
	Synthetic Aperture Radar (SAR) for imaging and interferometric studies	Externally mounted, low-profile planar antenna arrays mounted flush on the underside of the aircraft wings or fuselage, cables
	Airborne laser scanner/swath laser and laser altimeter	Nadir-directed viewport in fuselage, differential GPS, INS
	Digital photogrammetry camera	Differential GPS, INS, large (30") nadir-directed viewport
	Gravimeter	Mounting in center of gravity of aircraft, differential GPS positioning, autopilot
	Magnetometer (gradients?)	Non-magnetic sensor booms (3 m) at wing-tips, and/or non-magnetic tail boom, cables
	Imaging spectrometer	Differential GPS, INS, nadir-directed viewport in fuselage
Atmospheric Sciences	Temperature (reverse flow)	
	Pressure (e.g., Rosemount 1501)	
	Dew point/humidity (chilled mirror, licor for fluxes)	
	Liquid water (Gerber PVM100 also DMT LWC-100)	
	Cloud droplet spectra (FSSP-100)	
	Cloud droplet/precipitation (260x (one-D), 2D-C, 2D-P)	
	IR-surface temperature	
	Upwelling/downwelling shortwave and longwave radiation (spectroradiometers, Eppley PSP/PIR)	Up- and downward-looking viewports
	Standard chemical parameters	CO, O <sub>3</sub> , CO <sub>2</sub> , TDL H <sub>2</sub> O
	Photochemistry, reactive nitrogen and sulfur chemistry, and aerosol size and composition	Space for racks of mass spectrometers, laser systems, gas chromatographs, etc., with adjacent inlet mounting points for large inlets, under-wing hard points with a capacity of 100 lbs each near wing tips for particle measurements
	LIDAR	Co-aligned up- and down-looking viewports
	High-rate winds, temperatures (Friehe-type probe)	
	Dropsondes	Launch mechanism for expendable probes
	Miscellaneous remote sensing (e.g., Wyoming cloud radar)	

Table 4. Continued.

	Measurement or Sensor	Comments/Requirements
Oceanography and Sea Ice	Radiometers (sea and ice-surface temperatures with an accuracy of 0.02°C)	
	Surface salinity (new multiband microwave sensor being developed)	
	Multiband radiometers (sea-surface color)	
	Line scanner systems for ice thickness	
	Laser altimeter (ice freeboard and for altimetric work on shelf ice)	Nadir-directed viewport in fuselage, INS
	XBTs (temperature), XCTDs (temperature and conductivity) and XCVs (current velocity)	Launch mechanisms for expendable air-dropped probes
	Downward-looking, high-resolution digital cameras	Large nadir-directed viewport in fuselage, INS
	Solar radiation balance	Upward- and downward-looking sensors mounted above the fuselage between the wings and under the fuselage in the tail section. Positions have to be optimized to suppress shading effects by parts of the aircraft such as landing gear and rudder.
	Deployment of sea-ice buoys from aircraft	Launch mechanism, large cargo door
Navigation	Inertial navigation and GPS	GPS antennas and INS to determine aircraft geographic position, aircraft attitude (pitch, roll, and heading), horizontal and vertical components of aircraft ground speed
	Flight data recorder	Time
	Radar and laser altimeters to determine the aircraft's geometric height (altitude) above ground or water	Nadir-directed viewport and radome antenna

fications of the aircraft are needed to accommodate the various instruments, a schedule for the modification of the aircraft should be developed that is compatible with the specific missions planned for the aircraft. Mission planning will also require extensive coordination among the various groups wanting access to the platform. For example, the upload period for research missions is likely

to require one to two months and it is unlikely that major configuration changes will occur during an experiment due to this time constraint. This will require carefully developed payloads so that the greatest number of investigator can be accommodated during an experiment.

Developing an airborne research facility that serves the broad needs of the Antarctic community is a con-

siderable challenge. To be successful, it will require effective collaboration and coordination among a very interdisciplinary group of scientists in. It will also require initial and sustained support from the funding agency at a higher level than is typically done in grants for individual research projects. The results of the workshop indicate that such a facility is long overdue.

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# Relevant URLs

- FASTDRILL 2002 Workshop  
<http://www.es.ucsc.edu/~tulaczyk/fastdrill.htm>
- Frontiers and Opportunities in Antarctic Geosciences  
[http://www.mna.it/english/News/Antarctic\\_workshop/](http://www.mna.it/english/News/Antarctic_workshop/)
- International Polar Year 2007/08 (US site)  
<http://us-ipy.org/>
- International Polar Year 2007/08 (international site)  
<http://www.ipy.org/>
- National Science Foundation/Office of Polar Programs  
<http://www.nsf.gov/home/polar/>
- Remote Views and Exploration of Antarctic Lithosphere (REVEAL)  
<http://crustal.usgs.gov/antarctica>
- Research Aviation Facility NCAR  
<http://raf.atd.ucar.edu>
- Ross Island Meteorology Experiment (RIME)  
<http://polarmet.mps.ohio-state.edu/RIME-01/RIME.htm>
- Scientific Opportunities for a Long-Range Antarctic Research Aircraft (LARA)  
<http://polarmet.mps.ohio-state.edu/lara/>
- Assessing the Scope of Modifications for an LC-130 Hercules  
<http://www.ldeo.columbia.edu/~mstudying/LCSB/index.html>
- Structure and Evolution of the Antarctic Plate (SEAP)  
<http://www.antarcticarray.org/workshops.html>



# Appendix 1. Workshop Attendees

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# Appendix 2. Final Agenda

## MONDAY, 27 SEPTEMBER 2004 (SALON AB)

08:00 - 08:10 David Bromwich, Overview and Objectives of the Workshop  
08:10 - 08:30 Scott Borg, Remarks from NSF / OPP Perspective  
08:30 - 08:45 Waleed Abdalati, NASA's Perspective on Polar Remote Sensing

### Session 1: Solid Earth

08:45 - 09:45 Chair: Michael Studinger  
08:45 - 09:15 Carol Finn, REVEAL Overview  
09:15 - 09:45 Terry Wilson, Geology and Geophysics Science Goals

### Session 2: Glaciology

09:45 - 10:45 Chair: Bea Csatho  
09:45 - 10:15 Waleed Abdalati and Mark Fahnestock, Glacial Dynamics  
10:15 - 10:45 Ted Scambos, Remote Sensing for Ice Sheet Mapping  
10:45 - 11:00 COFFEE BREAK

### Session 3: Atmospheric Science

11:00 - 12:00 Chair: David Bromwich  
11:00 - 11:30 Tom Parish, Antarctic Airborne Atmospheric Science  
11:30 - 12:00 Fred Eisele, Airborne Atmospheric Chemistry

### Session 4: Oceanography/Sea Ice

12:00 - 13:00 Chair: Robin Muench  
12:00 - 12:30 Don Perovich, Sea Ice Studies  
12:30 - 13:00 Jamie Morison, Polar Physical Oceanography  
13:00 - 14:00 LUNCH BREAK, lunch on-site  
14:00 - 15:00 Poster Session  
15:00 - 17:30 Break-Out Discussion (Solid Earth, Glaciology, Atmospheric Science, Oceanography)  
Science Objectives, Sensors, Instrumentation, Data Collection (Sampling)  
18:00 - 20:00 Icebreaker – Hotel Prefunction Area / Salon A (cash bar)



## TUESDAY, 28 SEPTEMBER 2004 (SALON AB)

### Break-Out Group Reports

08:00 - 09:40 (15 min report + 10 min. discussion each)

Solid Earth: Michael Studinger

Glaciology: Bea Csatho

Atmospheric Sciences: David Bromwich

Oceanography, Sea Ice: Robin Muench

09:40 - 10:00 COFFEE BREAK

### Session 5: Capabilities and Opportunities of Research Aircraft

10:00 - 13:00 Chair: Robin Muench

10:00 - 10:30 Jeff Stith, NSF NCAR/RAF C-130Q and Candidate Aircrafts, HIAPER

10:30 - 10:45 Bill Krabill, NASA/WFF, Ice Sheet Mapping with Long Range Aircraft

10:45 - 11:00 John Brozena, NRL, Long-Range Wheeled Aircraft for Antarctic Science

11:00 - 11:15 John Holt, UTIG, Comparison of Airborne Platforms for Aerogeophysical Research in Antarctica

11:15 - 11:30 COFFEE BREAK

11:30 - 11:45 David Braaten et al., Univ. of Kansas, Advanced Radar Systems for Airborne Ice Thickness Measurements and Near-Surface Internal Layer Mapping

11:45 - 12:00 Christopher Zappa, LDEO, Toward a Modular Airborne Observing System for Antarctic Research

12:00 - 12:15 Terry McConnell, Magnetic Gradiometry

12:15 - 12:30 Tom Farr, NASA/JPL, Airborne Remote Sensing of Mars Analogue Sites in Antarctica

Followed by Discussion

13:00 - 14:00 LUNCH BREAK

### Session 6: Overview of Existing Aircraft Facilities: Models for Management Structure

14:00 - 15:30 Chair: Carol Finn

14:00 - 14:30 Gary Shelton, Overview on Existing Models

14:30 - 15:00 Heinz Miller, Alfred-Wegener-Institute Aircraft Operations: Case Studies and Lessons Learned

Followed by Discussion about Operation, Data Policies and Instrumentation

15:30 - 15:45 COFFEE BREAK

### Session 7: Desired Facility Model and Instrumentation

15:45 - 17:00 Chair: Robin Bell

15:45 - 16:00 Jerry Mullins, Research Applications of Airborne Digital Sensors and LIDAR systems

16:00 - Carol Finn, Summary and Opening of Discussion: Configuration, Instrument Maintenance, Operations, Data Reduction/Products

## WEDNESDAY, SEPTEMBER 29, 2004

### Session 8: Aircraft Operations and Safety Considerations for Polar Research Aircraft

08:00 - 09:00 Education of Scientists

08:00 - 08:30 Overview by Mike Scheuermann and Brian Stone  
Alternate Landing Sites, Weather Constraints, Range, Altitude, Payload,  
Conversion: Roll-on/Roll-off, Power  
Discussion

### Session 9: Data Policies, Data Management, Data Archiving

09:00 - 10:00 Richard Dirks and Jim Moore (NCAR), Data Management Considerations for the  
Dedicated Polar Research Aircraft  
Ted Scambos (NSIDC), Science Data Management for Antarctic Aerogeophysical Data  
from the Proposed Airborne Platform  
Discussion

10:00 - 11:00 **Panel Discussion:** Develop Road Map, Implementation Plan, Proposal Writing  
**Closing Remarks:** Bea Csatho

# Appendix 3. Poster Presentations

- Behlke, Rico (Uppsala Univ., Uppsala, Sweden), Airborne remote sensing campaign over Svalbard
- Behrendt, John (Univ. of Colorado, Boulder, CO), Use of LC-130 “Science” aircraft for long range aerogeophysical surveys in Antarctica, experiences from the late 1970s
- Blankenship, Donald (Univ. of Texas, Austin, TX) et al., Investigating the crustal elements of the central Antarctic Plate (icecap): How long-range-aerogeophysics is critical to understanding the evolution of the East Antarctic ice sheet
- Braaten, David (Univ. of Kansas, Lawrence, KS), Advanced radar systems for airborne ice thickness measurements and near-surface internal layer mapping
- Fahnestock, Mark (Univ. of New Hampshire, Durham, NH), The use of ice penetrating radar profiles for large area mapping of long-term accumulation and vertical strain rates: an example covering 10,000 line kilometers in Greenland
- Kim, Edward (NASA/GSFC, Greenbelt, MD), The Airborne Earth Science Microwave Imaging Radiometer (AESMIR)
- Lazzara, Matthew (AMCR/Univ. of Wisconsin, Madison, WI), The use of existing instrumentation on a long-range science aircraft for Antarctica
- Lubin, Dan (Scripps Institution of Oceanography, La Jolla, CA), Aircraft remote sensing of Antarctic cloud microphysical and radiative properties
- Matsuoka, Kenichi (Univ. of Washington, Seattle, WA), Polarimetric radar measurements of the interior ice to reveal ice-flow induced features
- Powers, Jordan (NCAR, Boulder, CO), Numerical weather prediction in Antarctica and a long-range aircraft for Antarctic research
- Shum, C.K., Chris Jekeli (OSU, Columbus, OH), Bea Csatho et al., Interdisciplinary Antarctic Research in Geodesy Using an Instrumented, Long-Range Aircraft
- Vogel, Stefan (BPRC, OSU, Columbus, OH) et al., Investigating the sub-glacial environment and geology of Antarctica by direct means, a new frontier in Antarctic research
- Von Frese, Ralph (OSU, Columbus, OH), Aerogeophysical Polar Explorer (Apex) for bi-polar lithospheric investigations
- Wilson, Doug and Bruce Luyendyk (UCLA, Santa Barbara, CA), Aerogeophysical survey of the continent-ocean transition of Pacific West Antarctica

# Appendix 4. Mission Scenarios

## REGIONAL AEROGEOPHYSICAL MAPPING

**Survey characteristics:** geophysical mapping (gravity, magnetics, laser, ice-penetrating radar) of large (>1000 x 1000 km) areas in the deep interior of the continent on a orthogonal grid of flight lines. Flight line spacing should be 10 km or less. Tie lines are usually spaced 3-4 times the flight line spacing.

**Particular aircraft requirements:** Radar antenna structures need to be mounted externally under the wings. A nadir directed viewport with defrost capability is required for the laser altimeter.

**Ground requirements:** 24x7 power and heat to aircraft. Refueling close to survey area.

**Locations:** deep interior of the continent, e.g., Gamburtsev Subglacial Mountains, continental margins that are inaccessible for ships due to sea-ice cover

Duration	Range	Altitude	Power	Space	Weight	Seats for Scientists
10+ hours	2500+ nm	500 m above surface	<10 kVA	3x19" racks	2.5 Klbs	3-4

## SEA ICE TRANSECT

**Survey characteristics:** Continuous mapping (laser altimeter, ice-penetrating active microwave, high resolution visual band) along cross-basin transects with the capability to air drop drifting buoys on the pack ice.

**Particular aircraft requirements:** Deployment of buoys from aircraft. Nadir directed openings through fuselage of aircraft.

**Ground requirements:** Aircraft access and refueling adjacent to survey area.

**Locations:** Ross Sea, Weddell Sea (need to land and refuel), Antarctic Convergence to continent.

Duration	Range	Altitude	Power	Space	Weight	Seats for Scientists
10+ hours	2500+ nm	1000 m above surface	10 kVA	2x19" racks	2.5 Klbs	4



## ANTARCTIC REGIONAL INTERACTIONS METEOROLOGY EXPERIMENT (RIME)

**Survey characteristics:** A wide variety of mission profiles will be needed from low-level, nearby flying to remote missions operating near the tropopause. A diverse array of sensors can be anticipated depending on the mission. Airborne deployment of instruments is also a desirable feature.

**Particular aircraft requirements:** Dropsonde capability.

**Ground requirements:** Some ground laboratory space. Access to aircraft sensors.

**Locations:** From/to McMurdo

Duration	Range	Altitude	Power	Space	Weight	Seats for Scientists
8-10 hours	2500+ nm	Low level to 400 mb	15 kVA	32x19" racks	5 Klbs	6

## ANTARCTIC CHEMISTRY INVESTIGATION (ANTCI)

**Survey characteristics:** In-transit measurements of *in situ* atmospheric chemistry plus up and down looking LIDAR measurements. Measurements location would be between South Pole and coastal sites and also into deep interior of the continent.

**Particular aircraft requirements:** 6 - 8 sampling ports, plus window ports, and up and down looking LIDAR and spectroradiometer ports. Under wing hard points for aerosol (large particle / droplet) measurements.

**Ground requirements:** Heated laboratory. 24x7 heat and power to aircraft (most instruments would not require 24x7 heat and power on the aircraft at McMurdo but probably would at the pole). Access to aircraft sensors.

**Locations:** Remote skiways.

Duration	Range	Altitude	Power	Space	Weight	Seats for Scientists
10 hours	2500+ nm	Mostly low level, some high level up to 7 km, and profiles in between	40 kVA	10x19" racks	10-12 Klbs	16

# GLACIOLOGICAL SURVEY OF INTERNAL LAYERING, OUTLET GLACIERS AND GROUNDING LINES

**Survey characteristics:** Profiling of surface elevation, internal layering (both near surface with broadband high frequency shallow radar, and through the entire ice thickness with a more conventional ice penetrating radar), ice thickness, and bed scattering characteristics along flight lines which may be oriented along flow lines, transverse to flow, and along previously determined elevation profiles. There are two likely flight scenarios: 1) long-range profiling at 400 m AGL of internal layering and ice thickness over the interior for recovery of accumulation and ice flow information, typically tied to earlier profiles or directly to ice core sites where the ice age-depth profile is known. Flights along flow lines are not required to retrieve this information, but in some cases could be beneficial. These flights would not likely be repeated unless they crossed rapidly flowing ice streams or outlet glaciers that might be changing. 2) Studies of remote outlet glaciers that may be rapidly changing – the flight plan here would use a high altitude transit to the site to save fuel and maximize the line kilometers that could be flown at ~400 m AGL over distant outlet glaciers, where the flight patterns would be along flow across the grounding line, and across flow at a number of points to determine channel geometries so that the flux of the system could be measured at a number of gates. Typically these flights over outlet glaciers would be repeated in one to a few years, so that changes in surface elevation (ice volume) could be measured.

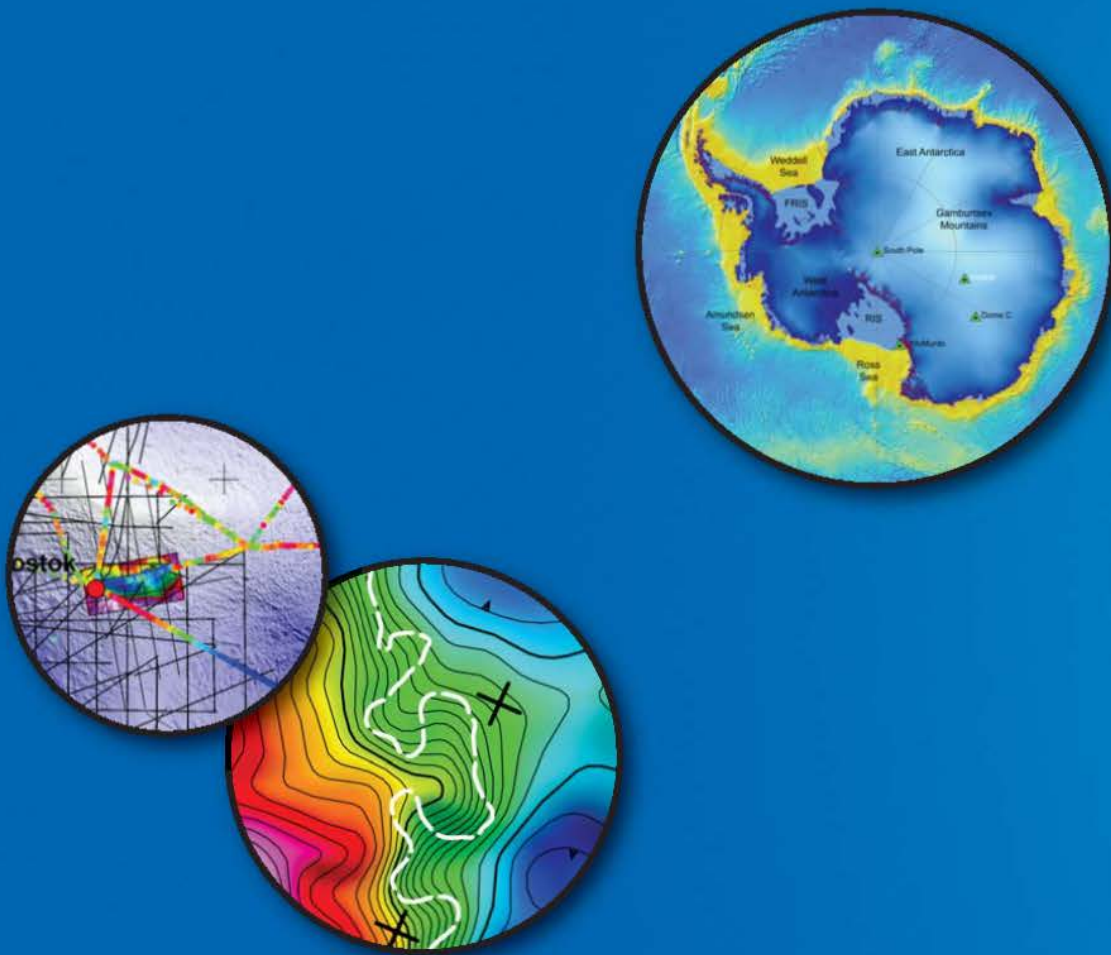
**Particular aircraft requirements:** Radar antenna structures need to be mounted externally under the wings, with the possibility of fuselage mounting for higher frequency radars. A nadir directed viewport (>16”) with defrost capability is required for a scanning laser altimeter, with precise pointing capability. The ability to fly the aircraft within ~30 m of previous or pre-determined flight lines is required, so that surface elevations will overlap spatially with earlier measurements.

**Ground requirements:** Heat and power to aircraft prior to flights. Access to aircraft sensors.

**Locations:** interior and perimeter of the entire Antarctic continent.

Duration	Range	Altitude	Power	Space	Weight	Seats for Scientists
10+ hours	2500+ nm	1) 400 m AGL on long profiles in the interior 2) 400 m on site, high elevation in transit to study sites	<10 kVA	2x19” racks	2.5 Klbs	3-4





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JULY 2005